2007

A Comparison Of Attentional Reserve Capacity Across Three Sensory Modalities

John Brill
University of Central Florida

A COMPARISON OF ATTENTIONAL RESERVE CAPACITY ACROSS THREE SENSORY MODALITIES

by

J. CHRISTOPHER BRILL
A.A. University of Cincinnati, 1993
B.A. Northern Kentucky University, 1996
M.A. University of West Florida, 2003

A dissertation in partial fulfillment of the requirements
for the degree of Doctor of Philosophy
in the Department of Psychology
in the College of Sciences
at the University of Central Florida
Orlando, Florida

Spring Term
2007

Major Professor: Richard D. Gilson

ABSTRACT

There are two theoretical approaches to the nature of attentional resources. One proposes a single, flexible pool of cognitive resources; the other poses there are multiple resources. This study was designed to systematically examine whether there is evidence for multiple resource theory using a counting task consisting of visual, auditory, and tactile signals using two experiments. The goal of the first experiment was the validation of a multi-modal secondary loading task. Thirty-two participants performed nine variations of a multi-modal counting task incorporating three modalities and three demand levels. Performance and subjective ratings of workload were measured for each of the nine conditions of the within-subjects design. Significant differences were found on the basis of task demand level, irrespective of modality. Moreover, the perceived workload associated with the tasks differed by task demand level and not by modality. These results suggest the counting task is a valid means of imposing task demands across multiple modalities.

The second experiment used the same counting task as a secondary load to a primary visual monitoring task, the system monitoring component of the Multi-Attribute Task Battery (MATB). The experimental conditions consisted of performing the system monitoring task alone as a reference and performing system monitoring combined with visual, auditory, or tactile counting. Thirty-one participants were exposed to all four experimental conditions in a within-subjects design. Performance on the primary and secondary tasks was measured, and subjective workload was assessed for each condition.

Participants were instructed to maintain performance on the primary task, irrespective of condition, which they did so effectively. Secondary task performance for the visual-auditory and visual-tactile conditions was significantly better than for the visual-visual dual task condition. Subjective workload ratings were also consistent with the performance measures. These results clearly indicate that there is less interference for cross-modal tasks than for intramodal tasks. These results add evidence to multiple resource theory. Finally, these results have practical implications that include human performance assessment for display and alarm development, assessment of attentional reserve capacity for adaptive automation systems, and training.

Dedicated to Ma.

ACKNOWLEDGMENTS

I want to offer my sincere gratitude to the following people for their time and assistance with this effort: Drs. Richard Gilson, Mustapha Mouloua, Ed Rinalducci, and Robert Kennedy.

I also would like to thank “honorary committee member” Dr. Joel Warm at the University of Cincinnati for his insightful comments during the early stages of this work. This dissertation would not have been the same without his assistance.

Several undergraduate research assistants were instrumental in helping me complete this study. The greatest thanks go to Sarah Woodard and Brooke Dovey, whose time and dedication were essential for completing this research. Research assistants Carla Landsberg and Megan Crossfield also deserve thanks for their help in the final stages of this work. Other research assistants who helped lay the foundation of this research are as follows: Mary-Elizabeth “Be-Be” Gonzalez, Mary Strickland, Kimberly Whitehead, Janine Quinn, and Sorrel Concodora.

Special thanks also go to Sherri Rehfeld and Cleve Mortimer for “paving the way” and tolerating an incalculable number of questions and nervous rants.

Last, but not least, I’d like to thank my patient and loving wife, Anita, who supported and inspired me throughout this work. You are no longer married to a professional student.

TABLE OF CONTENTS

LIST OF FIGURES x

LIST OF TABLES xi

CHAPTER 1: INTRODUCTION 1

A Single, Flexible Pool of Attention or Multiple Resources 2

Kahneman's Unitary Resource Model of Attention 3

Wickens' Multiple Resource Theory 6

Baddeley's Model of Working Memory 9

Neurophysiological Evidence for Multiple Resource Theories of Attention 10

Goals of the Present Research 13

CHAPTER 2: EXPERIMENT 1 14

Introduction 14

Research Hypotheses 15

Method 15

Participants 15

Apparatus and Materials 16

Design and Procedure 22

Results 24

Additional Analyses 27

Discussion 28

CHAPTER 3: EXPERIMENT 2 32
Introduction 32
Research Hypotheses 34
Method 35
Participants 35
Apparatus and Materials 35
Design and Procedure 37
Results 39
Primary Task Performance 40
Secondary-Task Performance 41
Perceived Workload Ratings 42
Additional Analyses 44
Discussion 46
CHAPTER 4: GENERAL DISCUSION 49
Applications of this Research 49
Limitations of the Present Research 52
Directions for Future Research 53
Summary 56
APPENDIX A: INSTITUTIONAL REVIEW BOARD APPROVAL LETTER 57
APPENDIX B: NASA-TLX INSTRUCTIONS AND SCRIPTS 59

APPENDIX C: ORDER-10 LATIN SQUARE DESIGN WITH TASK SEQUENCES 61

APPENDIX D: INFORMED CONSENT STATEMENT.. 63

APPENDIX E: DEMOGRAPHICS AND MEDICAL HISTORY FORMS.................... 67

APPENDIX F: EXAMPLE M-SWAP SCRIPTS WITH TASK INSTRUCTIONS AND COMPUTER COMMANDS 70

APPENDIX G: EXPERIMENT 1 SKEWNESS AND KURTOSIS STATISTICS FOR M-SWAP PERCENT CORRECT AND NASA-TLX SCORES................................ 74

APPENDIX H: MATB VISUAL MONITORING TASK INSTRUCTIONS 76

APPENDIX I: EXPERIMENT 2 SKEWNESS AND KURTOSIS STATISTICS FOR MATB PERCENT CORRECT, M-SWAP PERCENT CORRECT, AND GLOBAL NASA-TLX SCORES.. 78

REFERENCES 80

LIST OF FIGURES

Figure 1. A depiction of information processing from detection through attentional focus 3

Figure 2. Kahneman's Unitary Resource Model of Attention. 4

Figure 3. Wickens' Multiple Resource Model of Attention. 7

Figure 4. An over-the-shoulder perspective of the experimental setup with the wall-mounted visual display. 17

Figure 5. A Model C2 tactor secured to a Velstretch® belt 18

Figure 6. The three-button response box 19

Figure 7. The three-tactor array, as worn by a participant. 20

Figure 8. Theoretical model of resource consumption by M-SWAP across three sensory modalities and three task demand levels. 29

Figure 9. Theoretical model of spare capacity consumed by a primary task and a secondary loading task with three demand levels. 33

Figure 10. Screen capture of the system monitoring component of the MATB 36

Figure 11. Mean percent correct on M-SWAP as a function of condition. 42

Figure 12. Mean Global NASA-TLX scores by condition.. 43

LIST OF TABLES

Table 1. Descriptive Statistics for Percent Correct on M-SWAP as a function of Modality and Demand Level. 25

Table 2. Descriptive Statistics for Global NASA-TLX Scores across Condition. 26

Table 3. Descriptive Statistics for d-prime for M-SWAP Performance across Condition 27

Table 4. Descriptive Statistics for beta for M-SWAP Performance across Condition. 28

Table 5. Descriptive Statistics for Percent Correct on MATB across Condition 39

Table 6. Descriptive Statistics for Percent Correct on M-SWAP across Condition......... 40

Table 7. Descriptive Statistics for Global NASA-TLX Scores across Condition 40

Table 8. Mean Response Time for MATB Visual Monitoring Task across Condition.... 44

Table 9. Descriptive Statistics for d-prime for MATB Performance across Condition.... 44

Table 10. Descriptive Statistics for beta for MATB Performance across Condition........ 45

Table 11. Descriptive Statistics for d-prime for M-SWAP Performance across Condition 45

Table 12. Descriptive Statistics for beta for M-SWAP Performance across Condition. .. 46

CHAPTER 1: INTRODUCTION

When humans enter the world at birth, we are virtually blind. Our vision is coarse and unrefined, unable to resolve medium or high spatial frequencies. In this early phase of development, much of our knowledge of the world is acquired through the sense of touch – through feeling, grabbing, and mouthing. However, the dominance of touch diminishes as the distance senses develop further to the extent that we become primarily visual creatures (Schiffman, 1996). Empirically, this is exemplified through the visual dominance effect, which is a strong inclination to attend to visual inputs as compared to other modalities (Posner, Nissen, & Klein, 1976; Rock & Victor, 1964).

Notwithstanding, our other sensory modalities still verify reality and are essential to our survival. Binaural hearing facilitates the localization and identification of sound sources, informing the eyes where to look and what to expect (Blake & Sekuler, 2004). Once objects are close in proximity, the skin senses allow us to gather information about texture, temperature, or weight. Touch can also serve as an alerting mechanism, telling us when objects are in our immediate space, irrespective of gaze, masking noise, or smell. Despite our multi-modal nature, most technological interfaces rely primarily upon vision and secondarily upon audition. In many cases, system users are required to perform multiple tasks simultaneously that require coding and manipulating information presented through a single sensory modality, typically vision. However, if too much information is presented to that modality, the user's attentional capacity can be exceeded, resulting in performance decrements with potentially serious consequences. Attentional capacity limitations restrict the amount of information that is coded and moved into short-term or working memory (Robinson-Riegler & Robinson-Riegler, 2004). Any reduction in spare attentional capacity would manifest itself through primary performance measures or signal detection sensitivity (Parasuraman, 1979).

A Single, Flexible Pool of Attention or Multiple Resources

Attention has been long recognized as a limited capacity system (James, 1890). One way of managing these limitations is by shifting information from an overloaded sensory modality to one with untapped reserve capacity. However, this approach is rooted in two suppositions: 1) Attention is a limited capacity resource, and 2) Attentional capacity can be distributed among sensory modalities. Kahneman (1973) and Wickens (1984) review a number of studies that suggest when task demands are low, task performance is high, and when task demands increase, deficits in task performance likewise increase. Parasuraman (1979) found that increasing event rates in a signal detection task resulted in decreased signal detection sensitivity, which suggests that the observers' reserve attentional resources were depleted.

Figure 1 provides a basic graphical depiction of information-processing, which includes the role of attentional capacity. This depiction is largely a synthesis of information processing theories by Kahneman (1973) and Deutsch and Deutsch (1963). Stimuli are detected by the sense organs when their energetics sufficiently meet or exceed sensory thresholds. Information regarding the stimuli is coded and processed, which includes basic analyses of features such as intensity ranges, just noticeable differences

(JNDs), and according to late-selection theory, the stimuli are identified (Deutsch & Deutsch, 1963). These stimuli can then be selected for attentional focus; however, our ability to do so is contingent upon the availability of attentional capacity.

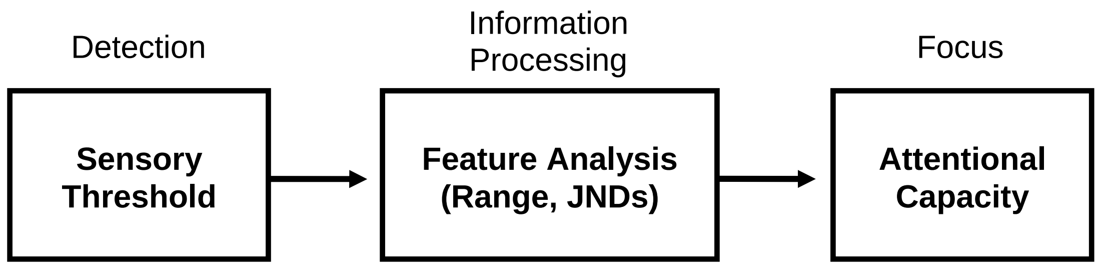

Figure 1. A depiction of information processing from detection through attentional focus.

Kahneman's Unitary Resource Model of Attention

Two major perspectives are pertinent to the study of attentional capacity. One is the unitary resource approach, which proposes that attention can be conceptualized as a single pool (Kahneman, 1973). Resources are drawn from the pool for different stages of information processing, and so long as spare capacity is available, they can be allocated towards any number of concurrent tasks (Moray, 1967). See Figure 2 for a depiction of Kahneman's Capacity Theory. Kahneman purports that any "interference between tasks is due to insufficient response of the system to demands, and to the narrowing of attention when effort is high" (p. 16). In other words, deficits in dual task performance result from task demands having exceeded the available capacity. The amount of available capacity varies, contingent upon factors such as arousal.

Kahneman acknowledges the presence of a modality effect, wherein it is more difficult to detect targets on the same modality versus different modalities. However, he stops short of actually dividing attentional resources by modality, suggesting that attention is simply divided flexibly across tasks. Subsequent incarnations of this notion are present in Norman and Bobrow (1975), Johnston and Heinz (1978), Navon and Gopher (1979), and more recently, Young and Stanton (2002).

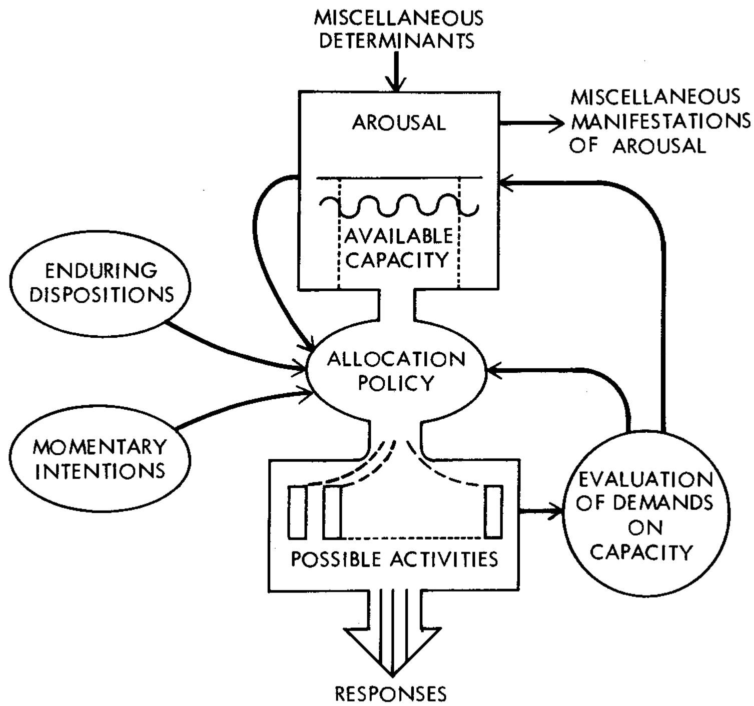

Figure 2. Kahneman's Unitary Resource Model of Attention. From D. Kahneman (1973). *Attention and Effort.* Englewood Cliffs, New Jersey: Prentice Hall.

Posner and Boies (1971) describe processing capacity as one of the three component processes of attention. The capacity view of attention is a popular one and serves as the basis for many empirical studies. For example, Proctor and colleagues conducted a series of studies examining attention and processing capacity using a dual-task paradigm consisting of a letter-matching task and various secondary tasks. Proctor

(1978) found that participants could not maintain an active visual-memory code while performing a visual addition task. He concluded that central processing was not critical for maintaining the visual memory code, but rather some modality-specific processing system associated with attending to visual stimuli must be responsible. In a subsequent investigation, Proctor and Proctor (1979) used visual letter-matching as a primary task and paired it with an auditory or a visual probe detection task. Participants were instructed they would receive probe signals exclusively visually or auditorily, but 25% of the time the probe signals were presented unexpectedly to a different modality. They found that participants could effectively detect unexpected auditory stimuli, but they lacked the capacity to process unexpected visual stimuli, presumably due to the demands of the primary visual task.

Duncan, Martens, and Ward (1997) compared attentional capacity limitations within and between vision and audition. Visual attentional capacity was tested using a detection task in which target words were embedded into streams of letter strings. Auditory attentional capacity was tested using a dichotic listening task in which streams of word sounds with embedded word targets were presented. A mixed-modality condition was employed in which a visual and an auditory stream were presented simultaneously. Target detection accuracy was significantly better for the mixed-modality condition as compared to the intramodal task conditions. Further, an additional "cost" in the form of time-locked interference was observed. For successive intramodal targets, a reduction in target detection performance lasting several hundred milliseconds was seen following each successful detection. This is consistent with Telford's (1931) psychological refractory period paradigm and the attentional blink phenomenon

(Raymond, Shapiro, & Arnell, 1992; Shapiro, Arnell, & Raymond, 1997). However, Duncan et al. did not observe the effect for cross-modal targets, suggesting that the depletion of attentional resources is modality-specific.

Talsma and colleagues found a similar result using the Rapid Serial Presentation Paradigm (RSVP; Talsma, Doty, Strowd, & Woldorff, 2006). They recorded evoked potentials during the presentation of visual, auditory, or audiovisual letter streams. Letter-stream-elicited steady-state evoked potentials were the largest for the audiovisual condition as compared to single modality conditions. Talsma and colleagues concluded that attentional capacity is larger between two modalities as compared to a single modality.

Wickens' Multiple Resource Theory

Perhaps the most prominent proponent of multiple resource theory is Wickens (1984, 2002) with his multiple resource theory of human performance. Although it is not a theory of attention, *per se*, it attempts to explain the modality effects observed in attentional research using dual tasks. Wickens' theory divides resources according to modalities, codes, stages, and responses (see Figure 3).

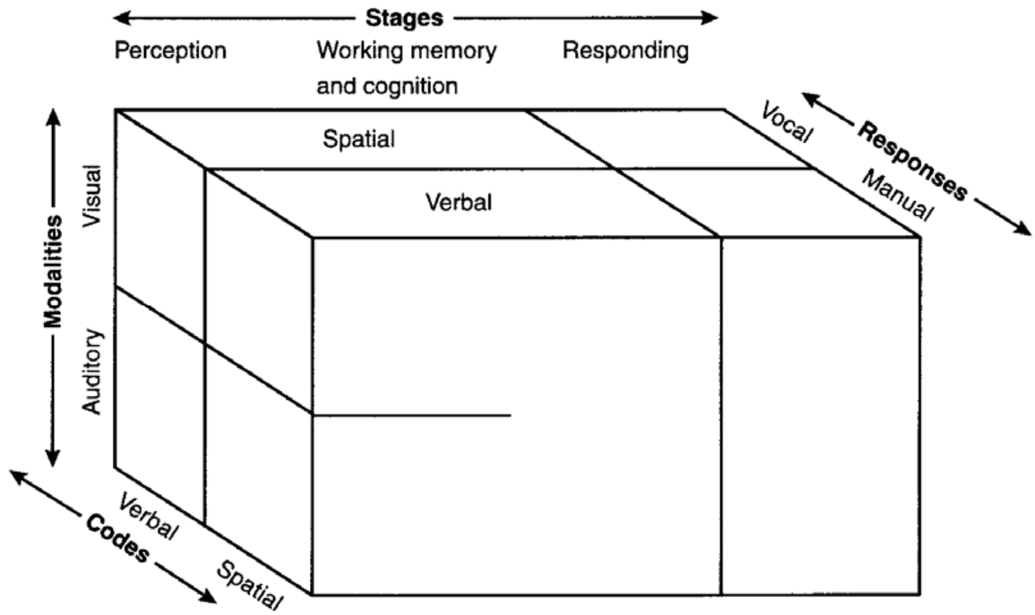

Figure 3. Wickens' Multiple Resource Model of Attention. From C. D. Wickens (1984). Processing resources in attention. In R. Parasuraman & R. Davies (Eds.), *Varieties of Attention* (pp. 63-102). London: Academic Press.

According to the classic model, a stimulus can be accepted through either the visual or auditory modality. The stimulus can be spatial or verbal in nature. Once perceived, it is coded as either a verbal or a spatial representation, and it enters the working memory stage of information-processing. A response to the stimulus is then generated, which can be manual or vocal. Any time tasks simultaneously tax a single resource, there is potential for interference and degraded performance. Consequently, the encoding of sensory information from two simultaneous tasks is more efficient when they do not share the same modality or central processing code. It explains why the performance of dual cross-modal tasks (e.g., visual-auditory) is generally easier and more efficient than the performance of dual intramodal tasks (e.g., visual-visual or auditory-auditory) . The implication present in Wickens' model is that attentional resources are allocated independently to each modality. It is noteworthy that, to date, his model is inclusive of vision and audition only. However, Wickens' omission of a tactile resource pool in his model is understandable, as it is likely due to the paucity of data comparing attentional capacity for vision, audition, and touch.

There is empirical evidence supportive of Wickens' model, particularly with regards to the performance benefits associated with cross-modal tasks as opposed to intramodal tasks. For example, a study by Wickens (1976) incorporated a primary tracking task paired with either an auditory detection task or a constant pressure haptic task. Participants used a control stick to keep a moving cursor over a stationary target in the center of an oscilloscope screen. A secondary auditory detection task was presented periodically, requiring participants to respond vocally when a near-threshold tone had been detected. Alternatively, a force application task was administered, requiring participants to maintain pressure on a force sensitive control using visual feedback presented on voltmeter display. He found that the auditory detection task interfered less with a manual tracking task than did a constant pressure task, even though it was deemed more difficult. The implication is that tracking and constant pressure tasks required the same modality, and consequently, competed for the same resources.

Findings from other studies also support multiple resource theory. For example, Spelke, Hirst, and Neisser (1976) found that participants could simultaneously read and comprehend a written message while listening and transcribing words presented auditorily. Rollins and Hendricks (1980) examined the simultaneous processing of visual and auditory verbal information. They found that when two auditory verbal messages are presented simultaneously, performance is enhanced when one of the messages is also presented visually. The implication is that two auditory verbal messages draw from the same resource pool, and presenting one of the messages visually facilitates tapping into an unused resource with available reserve capacity. Isreal (1980) found greater intramodal interference between simultaneous tracking and reaction time tasks as opposed to when the tasks were cross-modal. Likewise, Parkes and Coleman (1990) found evidence of intramodal resource competition. They presented guidance cues to drivers and found greater task interference from cues presented visually rather than auditorily. As driving is primarily a visual task, the finding that visual rather than auditory cues interfered with driving performance is consistent with Wickens' theory.

Baddeley's Model of Working Memory

There is a degree of commonality between Wickens' multiple resource theory and Baddeley's model of working memory (Baddeley, 1992; Baddeley & Hitch, 1974). Baddeley proposes a multi-modal division of working memory wherein visual/spatial information is maintained in the visuospatial sketchpad and auditory/verbal information is maintained in the phonological loop. The attentional energetics required for receiving sensory information, perceiving and coding it, and then directing it into the appropriate working memory component is the responsibility of the central executive. The model does not include any type of working memory representation for tactile information. Any form of tactile information would be recoded into a spatial and/or verbal representation. For example, a person reading Braille might retain information regarding the spatiotemporal pattern of running their fingertip over the raised bumps in the visuospatial sketchpad as a spatial representation. However, the person would also code those tactile patterns into verbal representations and maintain them in the phonological loop in order to remember what they had read. As such, it is logical that a tactile-specific component of working memory is not incorporated into the model.

It is important to note that the vestibular system and the chemical senses are not included in any of these models. Although these senses provide information critical to our survival, few display technologies make use of them. The few systems that appeal to the chemical senses are primarily low-bandwidth virtual environment systems to increase immersion. At the point of this writing, there are no known displays that provide informational inputs into the vestibular system. Consequently, these are beyond the purview of the current investigation.

Neurophysiological Evidence for Multiple Resource Theories of Attention

Although the cognitive and performance models do not directly address evidence of a trimodal division of resources, there is some evidence in the neurophysiological literature. The data suggest that multi-modal attentional mechanisms reside primarily in the cortical regions responsible for processing sensory input for the relevant modality, as opposed to some central mechanism (Burton, Sinclair, Hong, Pruett, & Whang, 1997). For example, Burton and Sinclair (2000) recorded average firing rates (AFRs) for neurons responding to vibrotactile versus auditory stimuli in an attentional task in monkeys. The monkeys were presented with simultaneous vibrotactile stimulation on both hands; however, they were trained to attend only to one of their hands. They found significantly greater levels of activity in the somatosensory cortex corresponding to the attended hand versus that of the unattended hand, even though both hands were presented simultaneously with identical vibrotactile stimuli. Further, the presentation of auditory cues (distractors) had little impact on AFRs for the attending hemisphere.

Driver and colleagues (e.g., Driver & Spence, 1998; Eimer & Driver, 2000; Eimer & Forster, 2003) have investigated cross-modal links in spatial attention between vision, audition, and touch. Driver and Spence (1998) propose that spatial attention arises in a task-relevant area of the brain and spreads to cortical regions representing other modalities. The implication here is that modality-specific attentional modules exist; however, these modules are interconnected and only act semi-independently. Macaluso, Frith, and Driver (2000) conducted a study using positron emission tomography (PET). Their participants engaged in a selective spatial attention task in which they were presented with either light flashes or vibrotactile stimuli. All signals were presented on the right side of the participant. Conditions in which they attended to tactile stimuli only with their eyes closed resulted in activity in the left superior postcentral gyrus. However, more widespread activity was seen when participants engaged in the same task with their eyes open, as the PET showed activity in the left intraparietal sulcus. When participants engaged in visual attentional tasks, activity was observed in the left intraparietal sulcus and left occipitotemporal junction. This research is supportive of Spence and Driver's (1998) notion that sustained attention can operate at either a cross-modal or an intramodal level. It is important to note that none of these investigations has examined all three modalities (i.e., vision, audition, and touch) simultaneously. For example, Malusco et al. (2000) used vision and touch, but not audition, and Eimer and Forster (2003) used touch alone.

Eimer, van Velzen, and Driver (2002) examined interactions in spatial attention for vision, audition, and touch; however, the visual signals only served as a cuing mechanism rather than as a signal in the primary detection task. They measured event-related potentials (ERPs) in a multi-modal attentional task in which auditory or tactile signals were presented to the left or right side of participants. The signal was preceded by a visual cue intended to direct their attention to the side and modality to which the target signal would be presented. During some trials, non-target signals were presented to an unattended side and modality. They found that ERP modulation was greatest for the side to which attention was cued. From a behavioral perspective, unattended signals could be ignored. However, the ERP evidence suggested interactions between sensory modalities. Specifically, visual and auditory ERPs were observed during touch-relevant tasks. During auditory-relevant tasks, visual ERPs were observed, but tactile ERPs were not. Eimer and colleagues (2002) concluded that selective attention must be both supramodal and multi-modal, consistent with Driver and Spence's (1998) aforementioned proposition of localized activity followed by a spread to adjacent cortical regions.

Although the research discussed above focuses on cortical activity, it is worth noting that the cerebellum has been implicated in attentional switching between modalities for time-dependent tasks (Allen, Buxton, Wong, & Courchesne, 1997; Courchesne et al., 1994). Moreover, it is also important to note that there are no cerebellar projections of taste and smell, suggesting that its function might be reserved for spatial senses. More recently, however, the role of the cerebellum in attentional switching has been called into question. For example, Ravizza and Ivry (2001) and

Bischoff-Grethe, Ivry, and Grafton (2002) suggest the role of the cerebellum might be for switching between alternative responses rather than between sensory inputs.

Goals of the Present Research

Although the evidence supports the concept of multi-modal attentional resources, no studies have sought to determine the relative capacities of these resource pools across three sensory modalities. Therefore, the primary goal of this investigation is a multi-modal comparison of the attentional capacities of vision, audition, and touch. However, one should not presuppose the independence of the resource pools. Therefore, the second goal of this research is to gather evidence regarding the relative independence of the resource pools.

CHAPTER 2: EXPERIMENT 1

Introduction

The first step toward evaluating attentional reserve capacity across three sensory modalities is to develop the methodology in order to do so. This requires a task that is capable of presenting information independently through vision, audition, and touch. It is equally important that the cognitive component imposed by this task should remain the same, irrespective of the modality of signal presentation. A task that can be adapted for this use is the Multi-Sensory Workload Assessment Protocol (M-SWAP). M-SWAP is a multi-modal complex counting task capable of presenting visual, auditory, and vibrotactile signals. It is an extension of the complex counting tasks developed by Jerison (1955, 1956), later expanded by Kennedy (1971), and integrated into the Performance Evaluation Tests for Environmental Research (PETER) battery (Kennedy & Bittner, 1980). More recently, Mouloua, Rinalducci, Hancock, and Brill (2003) used the visual component of the counting task to evaluate the workload associated with the use of telematic devices, such as cellular telephones and car stereos.

As it is a counting task, the cognitive component is identical, irrespective of the modality through which the targets are presented. Moreover, it is capable of presenting three levels of task demand, which offers additional flexibility for “filling” reserve attentional capacity under a variety of operating circumstances. Any performance differences on this task can potentially serve as an indication of differential attentional capacity, particularly if they are on the basis of sensory modality. A secondary goal of this experiment is to gather evidence to further validate the protocol through use of subjective workload measures.

Research Hypotheses

Given the theoretical nature of the complex counting task, the following hypotheses were generated:

- Performance differences would be dependent upon task demand, but not modality.
- Subjective ratings of workload would differ as a function of task demand and not modality.

Method

Participants

Prior to data collection, a power analysis was conducted. Assuming a desired power of .80, a medium expected effect size, and $\alpha = .05$, a minimum sample size of 24 would be required to observe an effect (Cohen, 1977). A sample of 36 undergraduate psychology students was recruited from the University of Central Florida. However, the data from four of these participants could not be used for the experiment due to performance issues related to one of the research tasks (see Results for more detail), paring the sample down to 32 (13 males, 19 females). Ages ranged from 19 to 36 years of age ($M = 22.1$, $SD = 3.6$). All were in good health, and none indicated the presence of any type of sensory or motor disability that might influence the results of the study.

Students were compensated with either money at the rate of $10/hour or extra course credit at the standard psychology department rate of one credit per half hour. This experiment was approved by the University of Central Florida Institutional Review Board (see Appendix A), and all participants were treated in accordance with the ethical guidelines for human use in research.

Apparatus and Materials

Multi-Sensory Workload Assessment Protocol (M-SWAP)

M-SWAP is a multi-modal counting task consisting of visual, auditory, and vibrotactile components and a response box. For the visual component, an InterAct color liquid crystal (LCD) mobile monitor was used. The display was 5 in. (measured diagonally) and was mounted on a wall 16 in. above a desktop surface at approximately eye level (see Figure 4) such that it subtended a visual angle of approximately 9.2° horizontally and 6.9° vertically.

Figure 4. An over-the-shoulder perspective of the experimental setup with the wall-mounted visual display.

The auditory component of M-SWAP was presented through Sennheiser Model HD-280 PRO studio headphones. The headphones incorporate a circumaural closed-back design, which provides 32 dB of attenuation to reduce ambient sounds.

The tactile component of M-SWAP was presented via a custom-built wearable vibrotactile display. It consisted of a 2 in. Velstretch® belt and three EAI model C2 Tactors (Engineering Acoustics, Inc. Winter Park, FL). The 17 g tactors incorporate a center-surround design such that a 7 mm plunger-like contactor is preloaded against the skin to provide sinusoidal vibration at 250 Hz with a maximum displacement of 1.02 mm. The contactor has 1 mm of separation from a non-moving surround provided by the tactor housing (see Gescheider, Capraro, Frisina, Hamer, & Verrillo, 1978). The tactors were secured to the belt using adhesive-backed Velcro® that had been stuck to the backs of the devices (see Figure 5).

Figure 5. A Model C2 tactor secured to a Velstretch® belt

Prior to the application of the Velcro®, a hole was punched into its backing to facilitate the movement of the center contactor. The use of Velcro® allows the tactors to be moved to provide a custom fit for the person wearing the belt.

The tactors were driven by an Instek® Model GFG-8210 Function Generator whose output was amplified using a Velleman Model P2637 Supermini 2.5-Watt Power Amplifier. This amplified signal was directed to a particular tactor via an 8-channel mechanical relay board with a parallel port PC interface (Model K74; www.kitsrus.com).

The response box consisted of three standard joystick-style momentary switches mounted onto the top surface of a plastic enclosure. The buttons were aligned in a row horizontally, with a spacing of 2 cm (3 cm from center of a button to the next adjacent button; see Figure 6). It was connected to a PC via a standard joystick game port.

Figure 6. The three-button response box.

M-SWAP is administered via proprietary software developed by RSK Assessments, Inc. It is capable of presenting the Jerison counting task (1955, 1956) via any combination of three modalities: vision, audition, and touch. The signals for visual counting consist of three white boxes arranged in a horizontal line against a blue background. Each subtends a visual angle of approximately 2.7° horizontally and 1.4° vertically from a distance of 25 in. The three signals flash for 250 ms in a random sequence with random interstimulus intervals such that each of the three signals was presented an average of five, six, or eight times per minute. The task has three levels of demand, which vary depending upon the number of information channels that must be monitored. For example, low demand visual counting requires participants to count the number of times white boxes are presented on the left side of the display and respond after every fourth signal by pressing the left response button. The moderate demand task requires participants to count two information channels simultaneously and independently (left and center boxes), and respond by pressing the appropriate button (left or center) after each fourth presentation, respectively. The high demand task is administered similarly; participants must count separately three channels and respond by hitting the appropriate button after the fourth presentation of each signal.

The auditory version of M-SWAP has three simple tones, each at a different frequency. The low tone is 100 Hz, and the middle and high tones are 900 and 1800 Hz, respectively. Auditory counting is performed in a similar manner as is described for the visual counting task, each signal presented at random for 250 ms. It also has three demand levels contingent upon how many of the three channels are monitored.

The tactile version of M-SWAP uses three loci of vibration as signals, each presented for 250 ms. Tactors are placed such that they are situated on the far left, center, and far right of the abdomen (see Figure 7).

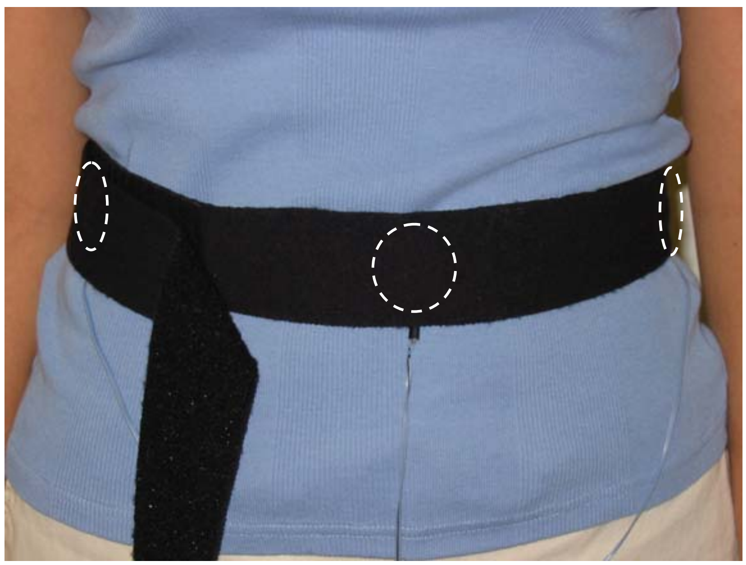

Figure 7. The three-tactor array, as worn by a participant. The dotted-lines show the approximate locations of the tactors.

The reasons for this configuration are two-fold. First, the spacing between loci is sufficiently wide to facilitate spatial discrimination, consistent with the findings of Cholewiak, Brill, and Schwab (2004). Second, the three-locus linear array is analogous to the spatial configuration of signals used in M-SWAP's visual component and the metaphoric configuration of the pitches used in M-SWAP's auditory component.

The M-SWAP software was run on a Gateway Solo Laptop Computer with a Pentium II 266 MHz processor, 32 MB system RAM, and 4 MB video RAM. The laptop had an integrated composite video output jack for sending the signal to the portable LCD display used for this experiment.

Research using an earlier incarnation of the visual and auditory counting tasks suggests test-retest reliability is .79 to .94 for 10-minute to 20-minute blocks (Kennedy, 1971; Kennedy & Bittner, 1980). Pilot testing suggests the test-retest reliability of the revised trimodal counting task is consistent with these data ($r = .96$ for five-minute blocks; Brill, Mouloua, Hancock, Gilson, & Kennedy, 2003).

NASA Task Load Index (NASA-TLX)

Subject workload was measured using Hart and Staveland's (1988) NASA Task Load Index (NASA-TLX), a paper and pencil questionnaire capable of providing global or multi-dimensional assessments of workload (see Appendix B for specific task instructions). The NASA-TLX is comprised of two components. First, participants rate mental demand, physical demand, temporal demand, effort, frustration, and performance using six visual-analog scales (VASs). Second, they make a series of pair-wise comparisons between the aforementioned descriptors. The VAS ratings are measured and converted to a percentage. The frequency with which each descriptor is selected in the pair-wise comparisons serves as a weighting mechanism for the VAS ratings and is used to calculate global workload. Using this standard scoring methodology, NASA-TLX scores can range from zero to one-hundred.

Design and Procedure

A 3 X 3 within-groups design was employed for this experiment (3 modalities X 3 demand levels). Participants performed all nine conditions (representing the nine variations of M-SWAP) plus a tenth "dummy" block wherein they performed the high-demand tactile counting task a second time. The order in which the tasks were performed was determined using an order-10 Latin Square (see Appendix C), a technique used to distribute more evenly carryover effects in repeated-measures designs (Williams, 1949). An order-10 Latin Square was desirable over an order-9 because it resulted in fewer sequence orders. An order-9 Latin Square produces 18 sequences, where as an order-10 produces 10 sequences. The desire to use the order-10 Latin Square necessitated the use of the "dummy" block. The use of the order-10 Latin Square was additionally advantageous as it reduced the overall *N* required to assign multiple participants to each task order.

Participants were welcomed to the laboratory and given a brief overview of the study. They were asked to read the informed consent statement (see Appendix D), given an opportunity to ask questions or voice any concerns, and signed the forms indicating their desire to proceed with the experiment. Participants then completed a demographics form and a basic medical history to ensure their eligibility for the experiment (see Appendix E). Persons with sensory or motor disabilities that might influence the results of the experiment (i.e., impaired or uncorrected vision, impaired hearing, reduced tactile sensitivity, or impaired motor functioning affecting the arms, hands, or digits) were excluded from participation in the study and offered minimal compensation for their time.

For people who were eligible to continue participating in the study, their girth was measured at a height of approximately 1 in. above the navel using a standard tailor's cloth measuring tape. These data were recorded and divided by four, resulting in each individual's metric for spacing tactor loci on the M-SWAP vibrotactile display. Participants were then asked to change into a 5.7 oz 100% white cotton t-shirt. The t-shirts were used to ensure standardization of the material between the tactors and the skin. They were instructed to avoid selecting a t-shirt that was too large so as to avoid wrinkles and folds in the material that could affect vibrotactile sensitivity. The experimenter left the room and closed the door in order to give the participant privacy to change into his or her t-shirt. The room was also locked from the outside to prevent an accidental intrusion. Once a participant finished changing, the vibrotactile belt was placed onto the abdomen at a height of 1 in. above the navel and stretched until slightly snug, such that the tactors were loaded against the skin with approximately 50 g of force. Participants were then seated for the duration of the experiment at a small desk that was placed against a wall.

Next, participants engaged in a cross-modal matching procedure to ensure that the signals were equated for perceptual loudness (Stevens, 1959). Participants donned headphones and were presented with visual and auditory signals from M-SWAP. Using the method of adjustment, a standard psychophysical technique (Fechner, 1860, as cited in Green & Swets, 1966), participants were instructed to use the volume knob on the laptop computer running the M-SWAP software to make the auditory tones as loud as the visual blocks were bright. Once the participant indicated satisfaction with the adjustment, the experimenter restarted the task and presented visual and tactile signals.

Participants were instructed to make the tactile signals as perceptually loud as the visual blocks were bright. To minimize the influence of acoustic cues associated with the vibrotactile display, participants wore foam earplugs and inactive studio headphones simultaneously. When asked, none indicated being able to hear anything, including the sound signature of the tactors.

Once participants finished the cross-modal matching procedure, they were given instructions for M-SWAP (see Appendix F). They engaged in three practice blocks, each lasting one minute, in which they performed the low demand visual, auditory, and tactile counting tasks, respectively. Participants who reached 100% performance by the end of the third practice block were permitted to proceed with the experiment.

Participants were then presented with ten blocks of the counting task. Each block was five minutes in duration. After each block, participants were asked to complete the NASA-TLX to rate their perceived workload for the task they had just performed.

Once the experiment was completed, participants were given privacy once again to change out of the laboratory t-shirt and into their regular clothes. They were debriefed and were given the option of signing up for a follow-up experiment. The total duration of the experimental session was 90 minutes.

Results

The data were screened for normality and equal variance (see Appendix G for skewness and kurtosis statistics). Data screening indicated that four participants were statistical outliers and were skewing the data; their performance on the 3-channel auditory counting task approximated three standard deviations from the sample mean.

Further, a note had been made in these participants' files on the basis of comments they had made during the experiment debrief regarding their ability to discriminate the auditory tones. As a result, these participants' data were excluded from all analyses.

The data output from the M-SWAP software provides each participant's hits, misses, and false alarms for each task performed. These data were compared against the total number of signals presented to derive the number of correct rejections. Raw frequencies of hits, misses, false alarms, and correct rejections were then converted into a proportional rate. These data were then used to calculate percent correct as the primary metric of counting performance. The descriptive statistics are presented in Table 1.

Table 1. *Descriptive Statistics for Percent Correct on M-SWAP as a function of Modality and Demand Level.*

	Modality								
Demand Level	Visual			Auditory			Tactile		
	M	*SD*	*N*	*M*	*SD*	*N*	*M*	*SD*	*N*
Low	.94	.06	32	.95	.10	32	.95	.05	32
Moderate	.89	.10	32	.88	.13	32	.90	.09	32
High	.83	.12	32	.80	.13	32	.84	.14	32

All statistical analyses were performed at an alpha level of .05 unless otherwise noted. A 3 X 3 repeated-measures analysis of variance (ANOVA) was computed for percent correct on the counting task. The independent variables were modality (visual, auditory, and tactile) and task demand level (low, moderate, and high). Task order was coded and treated as an experimental variable to test for the presence of carryover effects. The results indicate a main effect of task demand level, $F(2, 60) = 26.7$, $p < .001$, $\eta^2 =$

.46. No main effect of modality, $F(2, 60) = 0.16$, $p > .05$, $\eta^2 = 0.002$, and no interactions between modality and task demand level were observed, $F(4, 120) = 1.0$, $p > .05$, $\eta^2 = 0.01$. Further, no interactions between demand level and task order were found, $F(2, 60) = 0.15$, $p > .05$, $\eta^2 = 0.002$.

Planned comparisons were computed and indicated that, irrespective of modality, percent correct was significantly higher at the low task demand level than at the moderate or the high task demand levels, as was predicted. Further, percent correct for the high task demand condition was significantly lower than either of the other two task demand conditions, $t(248) = 5.48$, $p < .001$.

The NASA-TLX questionnaires were scored and global workload ratings were computed. The descriptive statistics are presented in Table 2.

Table 2. *Descriptive Statistics for Global NASA-TLX Scores across Condition.*

	Modality								
Demand Level	Visual			Auditory			Tactile		
	M	*SD*	*N*	*M*	*SD*	*N*	*M*	*SD*	*N*
Low	31.1	17.6	32	29.3	19.0	32	33.9	19.3	32
Moderate	48.1	21.2	32	52.1	21.6	32	52.6	19.9	32
High	66.7	18.7	32	67.9	18.6	32	65.3	18.7	32

A 3 X 3 repeated-measures ANOVA was performed for workload ratings for the counting task. As with the previous analysis, the independent variables were modality and task demand level. A significant main effect of demand level on workload ratings was observed, $F(2, 60) = 139.4$, $p < .001$, $\eta^2 = .81$. No main effect of modality, $F(2, 60) = 0.77$, $p > .05$, $\eta^2 = .001$, and no interactions between modality and task demand level were observed, $F(4, 120) = 1.17$, $p > .05$, $\eta^2 < .001$. Also, no interactions between demand level and task order were found, $F(2, 60) = 0.21$, $p > .05$, $\eta^2 < .001$.

Planned comparisons indicated that, across modalities, perceived workload was significantly lower for the low task demand conditions than for the moderate and high task demand conditions. Further, the perceived workload for high demand conditions was significantly higher than for the low or moderate demand conditions, $t(248) = 8.10$, $p < .001$.

Additional Analyses

Traditional signal detection metrics of sensitivity (*d*') and response bias (β) were calculated (see Macmillan & Creelman, 2005) for M-SWAP signal detection data from all nine conditions, the means for which are presented in Tables 3 and 4.

Table 3. *Descriptive Statistics for d-prime for M-SWAP Performance across Condition.*

	Modality								
Demand Level	Visual			Auditory			Tactile		
	M	*SD*	*N*	*M*	*SD*	*N*	*M*	*SD*	*N*
Low	4.24	1.59	32	4.59	1.45	32	4.67	1.33	32
Moderate	3.40	1.56	32	3.50	1.80	32	3.37	1.56	32
High	2.31	1.16	32	2.07	1.27	32	2.77	1.56	32

Table 4. *Descriptive Statistics for beta for M-SWAP Performance across Condition.*

Demand Level	Modality								
	Visual			Auditory			Tactile		
	M	*SD*	*N*	*M*	*SD*	*N*	*M*	*SD*	*N*
Low	1.06	0.99	32	1.13	1.48	32	0.83	0.86	32
Moderate	1.09	1.07	32	0.83	1.02	32	1.03	0.86	32
High	1.96	1.97	32	1.49	1.19	32	1.13	1.01	32

A 3 x 3 repeated-measures ANOVA was computed with d-prime as the dependent variable; demand and modality were the independent variables. A significant main effect of demand was found, $F(2, 60) = 17.4$, $p < .001$, $\eta^2 = .37$. No main effect of modality was found, and no interactions with task order were observed. Post hoc analysis (LSD) showed that d-prime for low demand counting was significantly higher than that of moderate counting, which was higher than that of high demand counting ($p < .001$). An ANOVA of beta values could not be performed because of wide differences in variability, which violated the assumptions for the test.

Discussion

The results clearly indicate that M-SWAP imposes demand differentially depending upon how many channels one counts, suggesting the demand manipulation was successful. In addition, the failure to find a main effect of modality of the primary task is equally as interesting, as it bodes well for the use of M-SWAP in applied contexts. The presence of significant modality effects would have indicated that the demand imposed by the visual, auditory, and tactile counting tasks is not equivalent, rendering any cross-modal comparisons unfair. However, these differences were not observed, and given the small effect size ($\eta^2 = .01$), a substantially large sample size would be required to find one, making the probability of committing a Type II error increasingly likely. Consequently, it is reasonable to conclude that performing M-SWAP consumes approximately the same quantity of cognitive resources, irrespective of the modality, so long as comparisons are made within the same task demand level. This conclusion is bolstered by the pattern observed in the subjective workload data, wherein differences were found on the basis of task demand level and not modality. These data followed a predictable ascending stair-step pattern as task demand level increased, which is supportive of the validity of the counting task. A graphical model conceptualizing the demand imposed by M-SWAP by modality can be seen in Figure 8.

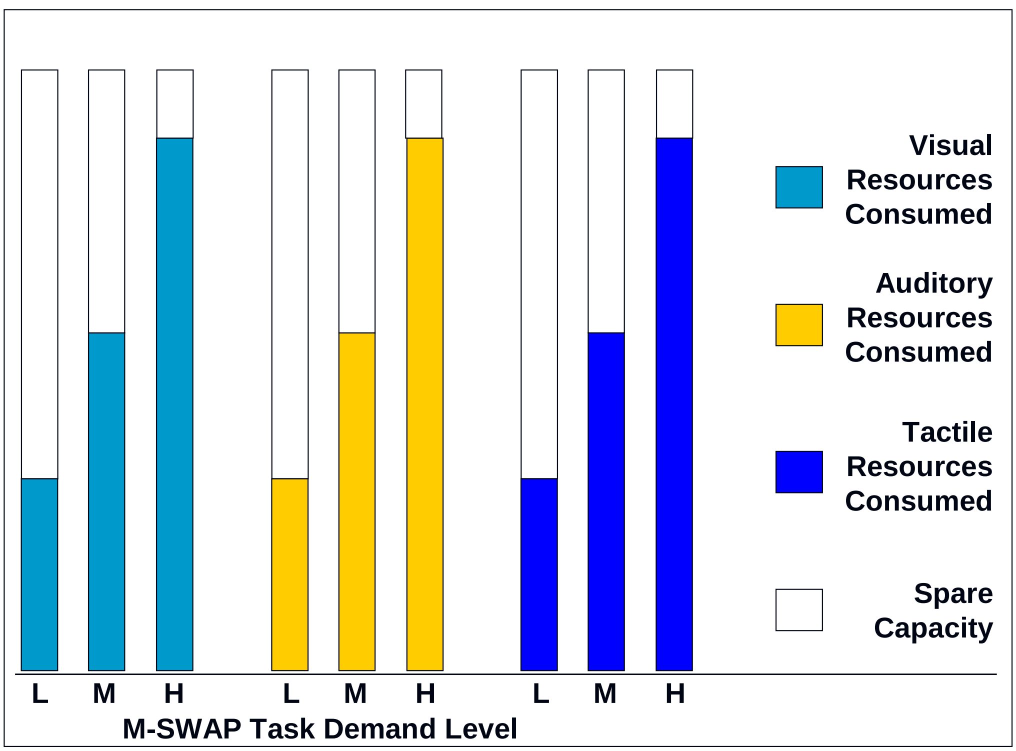

Figure 8. Theoretical model of resource consumption by M-SWAP across three sensory modalities and three task demand levels.

The significant differences in sensitivity are also interesting. They suggest that increases in task demand levels led to a reduction in spare capacity, which manifested in the form of decreased sensitivity. Although no *a priori* hypotheses were made with regards to sensitivity, these results are logical. It suggests that as demand levels increased, attentional capacity for accepting incoming sensory information decreased. It would be interesting to determine if increasing signal strength in the high demand conditions would improve sensitivity. However, this seems an unlikely scenario; the signals used in this research are already at superthreshold levels, and the increased "noise" resulting in decreased sensitivity is cognitive in nature (from workload) rather than issues of sensation.

From a theoretical perspective, these results neither suggest nor preclude the existence of multiple resource pools. The data can be explained from two equally valid perspectives:

1) Performing the multi-modal counting task draws the same quantity of resources, each from its respective pool.

2) Performing the multi-modal counting task draws the same quantity of resources, but each is drawing from a unitary resource (e.g., Kahneman, 1973).

The key to assessing whether multiple resource pools exist is to test multi-modal attention in a dual task situation. The results of this first experiment suggest that M-SWAP is a valid loading task for differentiating reserve capacity across sensory modalities. However, further investigation is required to determine whether drawing resources away from one pool results in a reduction of capacity in another, which is the goal of the second experiment.

CHAPTER 3: EXPERIMENT 2

Introduction

Although there is some evidence supporting multiple resource theories, the issue is far from settled. Nonetheless, human factors practitioners must deal regularly with issues of resource availability and attentional reserve capacity. One method of measuring attentional reserve capacity is the secondary-task technique. The technique is rooted in the assumption that the performance of a primary task will consume a certain amount of resources. The notion is that if the operator is capable of performing the task more or less perfectly, it is likely that some residual attentional capacity exists. In order to determine how much reserve capacity is present, a secondary task is loaded to consume the remaining resources. The approach requires that operators attempt to maintain performance on the primary task and only perform the secondary loading task with any remaining resources. If the operator can perform both the primary and secondary tasks perfectly, then some reserve capacity must be present. Under this scenario, the secondary task demand level can be increased in order to determine how much reserve capacity is present. A model depicting the relationships between available capacity, primary-task demand levels, and three secondary loading task demand levels is shown in Figure 9. The amount of available capacity shown in the model is fixed; however, in reality this amount can change based upon a variety of factors, such as task proficiency, fatigue (Hancock & Warm, 1989) or arousal levels (Kahneman, 1973).

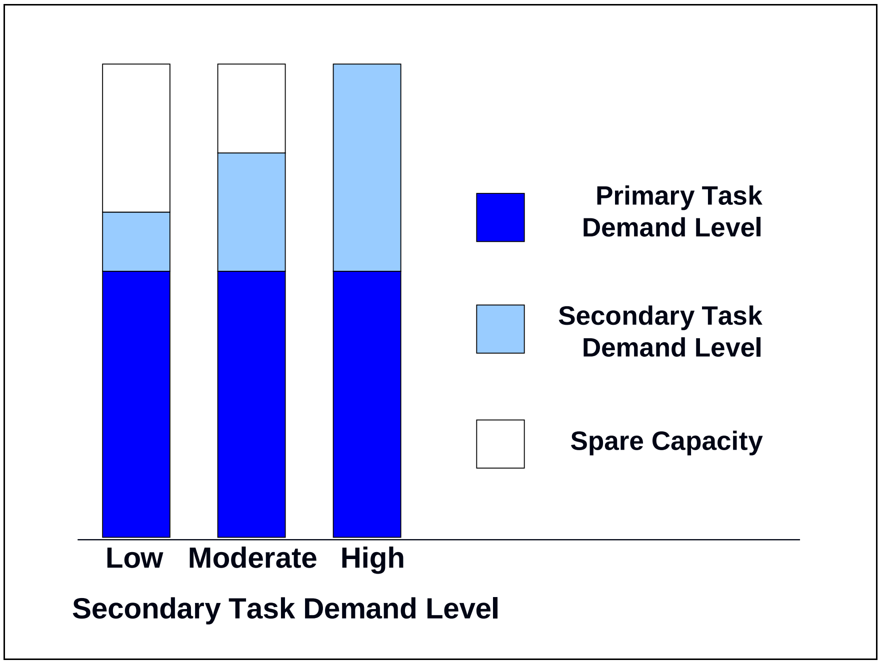

Figure 9. Theoretical model of spare capacity consumed by a primary task and a secondary loading task with three demand levels.

One way of determining whether multi-modal attention is divided into multiple pools versus a unitary resource is through use of this secondary task approach: tax one sensory modality with a task and then place demands successively upon the other remaining modalities with a secondary task. If the secondary task imposes demand equally across sensory modalities, any differences in secondary task performance would suggest differential reserve capacity (i.e., multiple pools of varying sizes). However, if no modality effects are observed, the results can potentially be interpreted from both unitary resource and multiple resource perspectives.

The approach taken here is that of a traditional dual task protocol (e.g., Ogden, Levine, & Eisner, 1979; Rolfe, 1973). A primary visual task is performed, and a secondary loading task is added periodically. The secondary task can either share or appeal to a different sensory modality from that of the primary task. Even though a secondary task is added, participants are asked to maintain performance on the primary task.

For the purposes of this experiment, the primary task is a visual monitoring task. M-SWAP will serve as a secondary loading task. The clear advantage of using M-SWAP in this context is the ability to present a secondary task to any of three modalities while imposing a consistent level of task demand.

Research Hypotheses

Assuming that performance on the primary task was maintained at a consistent level, irrespective of the presence of a secondary task, the following was predicted:

- Auditory and tactile counting task performance would be significantly better than visual counting task performance, as simultaneously performing two visual tasks would draw from the same resource.
- It was not known whether differences would be observed between auditory and tactile counting performance. Finding a performance difference would offer support for multiple resource theories of attention. Simultaneously failing to find differences and observing a low effect size can be interpreted as support for the unitary resource model.
- Subjective workload ratings for performing two intramodal tasks would be significantly higher than ratings for two cross-modal tasks or performing one task.

- It was not known whether differences would be found between subjective workload ratings for auditory and tactile counting.

Method

Participants

A sample of 35 undergraduate psychology students was recruited from the University of Central Florida. However, due to the aforementioned outlier issue, four participants were excluded from all analyses, resulting in $N = 31$ (13 males, 18 females). All had participated in the previous experiment. Ages ranged from 19 to 36 years of age ($M = 21.8$, $SD = 3.3$). All were in good health, and none indicated the presence of any type of sensory or motor disability that might influence the results of the study. Students received their preference of either money at the rate of $10/hour or extra course credit at the standard psychology department rate of one credit per half hour as compensation for their participation.

Apparatus and Materials

Multi-Attribute Task Battery

The system monitoring component of the Multi-Attribute Task Battery (MATB; Comstock & Arnegard, 1992) served as the primary visual task for this experiment (see Appendix H for task instructions). It consists of four bars arranged horizontally, each with a fixed scale and a moving pointer that represents the temperature and pressure gauges for two engines of an aircraft (see Figure 10).

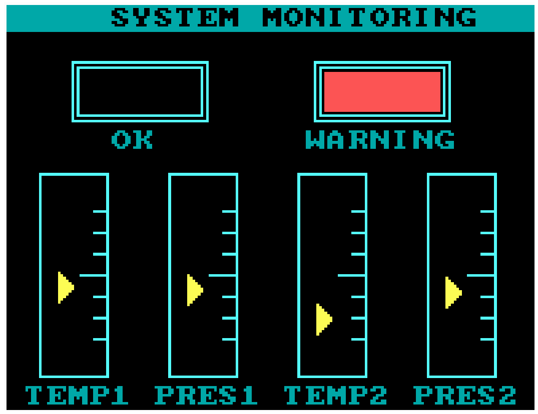

Figure 10. Screen capture of the system monitoring component of the MATB.

The gauges normally move up and down independently from one another within two tick marks of the center line, indicating normal operation. If a gauge moves outside this safe region, the participant resets it by hitting the appropriate key on a standard PC keyboard. The first four function keys of a standard QWERTY PC keyboard are mapped to the four gauges to facilitate participants' responses and reduce confusion.

A red light is present to serve as an alarm, indicating when one of the gauges moves out of the safe range. However, the reliability of this alarm is adjustable, allowing the experimenter to manipulate the demand imposed by the task. Alarm unreliability forces participants to monitor the gauges rather than monitoring the indicator light and then scanning the gauges. For the present experiment, the alarm reliability was set at 60%. This value was chosen based upon the results of pilot testing. As the visual monitoring task was serving as a primary task in a dual-task experimental paradigm, a moderate amount of task demand was required; however, the monitoring task could not be too demanding or participants would not have any reserve capacity to allocate to a secondary task.

The MATB monitoring task was presented on a Dell 17 in. LCD monitor. The monitor was positioned on a desk such that the monitoring task was positioned below the LCD presenting the M-SWAP visual counting task (see previous apparatus and materials section for specific details regarding the positioning of the M-SWAP visual display). This positioning was chosen because it was the closest possible placement of the two visual displays to facilitate dual task performance (Wickens, 1984).

Multi-Sensory Workload Assessment Protocol (M-SWAP)

M-SWAP served as the secondary task for this experiment. See the apparatus and materials section for the previous experiment for specific details regarding this task.

NASA-Task Load Index (TLX)

Global subjective workload ratings were assessed using the NASA-TLX. See the apparatus and materials section for the previous experiment for specific details.

Design and Procedure

A four-condition completely within-groups design was used for this experiment. The order in which the four conditions were present varied using an order-4 Latin Square. Participants were randomly assigned to a task order using a random number generator prior to the experiment.

Since this was the second experiment in the series, all participants had previously been in the laboratory. They were welcomed back and reminded that their participation was voluntary. Participants changed into a laboratory t-shirt, were fitted with the tactile belt, and were seated at a desk. Participants engaged in the cross-modal matching procedure for M-SWAP, as was described for the previous experiment.

Participants were given instructions for M-SWAP and performed three 1-minute blocks as practice. Each block presented one of the three modalities, but only at the moderate task demand level. A moderate task demand level was chosen based upon the results of pilot testing and to avoid ceiling and basement effects.

After practicing M-SWAP, participants were given instructions for the visual monitoring task of the MATB. They engaged in a five minute practice block at 60% alarm reliability and were permitted to proceed with the experiment if their performance met or exceeded 90%.

Participants were then asked to perform the MATB monitoring task, and they were told that the counting task would be presented periodically. They were instructed to perform the counting task, if possible, but only if it did not take away from performing the MATB monitoring task. The MATB monitoring task was presented for 20 minutes, which was divided into four five-minute blocks, each representing an experimental condition. One block consisted of performing the MATB monitoring task by itself. The remaining three blocks consisted of performing simultaneously the MATB monitoring task and each of the three M-SWAP modalities at moderate demand. After each block, the MATB monitoring task was paused, and participants were asked to complete the NASA-TLX for that block.

After the experiment, participants were given privacy to change back into their regular clothing. They were debriefed regarding the full purpose of the experiment series and thanked for their participation. The total duration of the experiment was approximately one hour.

Results

The data were screened for normality and equal variance (see Appendix I for skewness and kurtosis tables), which resulted in the exclusion of the same four outliers as occurred in the previous experiment (see the previous Results section). The primary metric for MATB monitoring performance was percent correct, which was calculated for each block based upon traditional signal detection data (i.e., hits, misses, false alarms, and correct rejections). Percent correct was calculated for all three M-SWAP blocks in the same manner as described for the previous experiment. The NASA-TLX questionnaires were scored using standard procedures to obtain global workload ratings (see Tables 5 -7 for the descriptive statistics for these measures).

Table 5. *Descriptive Statistics for Percent Correct on MATB across Condition*

Condition	*M*	*SD*	*N*
Single Task, No Counting	.94	.09	31
Dual-Task, Visual Counting	.88	.13	31
Dual-Task, Auditory Counting	.92	.13	31
Dual-Task, Tactile Counting	.92	.08	31

Table 6. *Descriptive Statistics for Percent Correct on M-SWAP across Condition*

Condition	*M*	*SD*	*N*
Dual-Task, Visual Counting	.68	.13	31
Dual-Task, Auditory Counting	.77	.15	31
Dual-Task, Tactile Counting	.80	.13	31

Table 7. *Descriptive Statistics for Global NASA-TLX Scores across Condition*

Condition	*M*	*SD*	*N*
Single Task, No Counting	40.0	20.2	31
Dual-Task, Visual Counting	77.7	13.1	31
Dual-Task, Auditory Counting	69.4	17.6	31
Dual-Task, Tactile Counting	67.9	20.6	31

Primary Task Performance

As was done in the first experiment, all data analyses were performed at an alpha = .05. A repeated-measures ANOVA was performed with percent correct on the MATB monitoring task as the dependent variable and experimental condition as the independent variable. Task order was coded and treated as a second independent variable to test for the presence of carryover effects. No main effect of condition, $F(3, 90) = 1.71$, $p = .170$, $\eta^2 = .05$, and no interactions between task condition and task order were observed, $F(9, 81) = 1.79$, $p > .05$, $\eta^2 = .015$.

Secondary-Task Performance

A repeated-measures ANOVA was performed with percent correct on M-SWAP as the dependent variable and experimental condition as the independent variable. A significant main effect of experimental condition was found, $F(2, 90) = 10.66$, $p < .001$, $\eta^2 = .29$. Planned comparisons were made based upon the *a priori* hypothesis that auditory and tactile counting performance would be significantly better than visual counting performance. The hypothesis was supported: percent correct was significantly lower for visual counting ($M = .65$, $SD = .13$) than for either auditory ($M = .75$, $SD = .15$) or tactile counting ($M = .78$, $SD = .13$), $t(60) = 4.52$, $p < .001$. No differences were expected (nor were they found) between the percent correct for auditory and tactile counting, $t(60) = 0.90$, $p = .347$. See Figure 11 for a graphical depiction of these results. No interactions between percent correct and task order were observed, $F(6, 52) = 0.85$, $p > .05$, $\eta^2 = .09$.

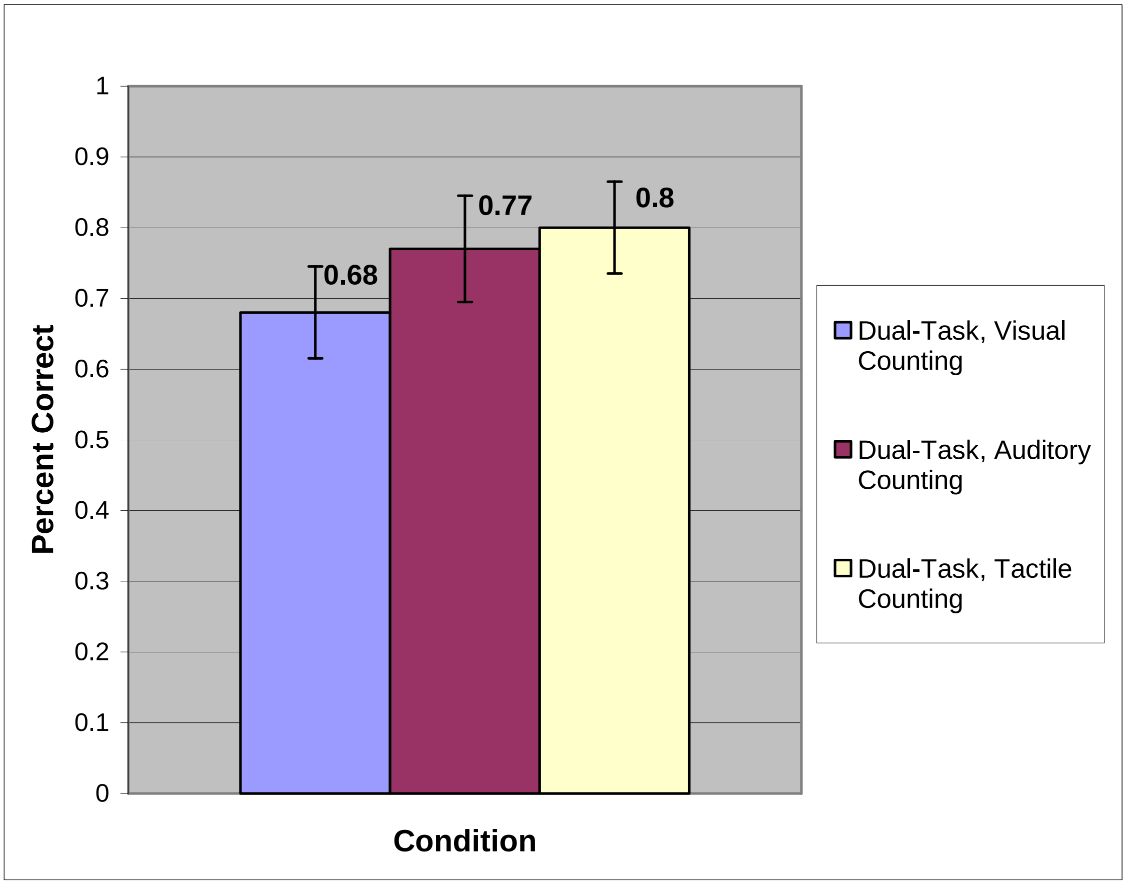

Figure 11. Mean percent correct on M-SWAP as a function of condition. The error bars represent standard deviations.

Perceived Workload Ratings

The NASA-TLX scores were also analyzed using a repeated-measures ANOVA. A significant main effect of experimental condition was observed, $F(3, 90) = 54.2$, $p < .001$, $\eta^2 = .39$. Planned comparisons tested, and subsequently confirmed, the hypothesis that workload ratings for the "no counting" MATB condition ($M = 40.0$, $SD = 20.2$) were significantly lower than that of the dual task conditions using visual counting ($M = 77.6$, $SD = 13.1$), auditory counting ($M = 69.4$, $SD = 17.6$), or tactile counting ($M = 67.9$, $SD = 20.6$), $t(90) = 12.31$, $p < .001$. Further, workload for the dual task condition with visual counting was rated significantly higher than for the dual task conditions with auditory or tactile counting, $t(90) = 3.30$, $p < .01$ (see Figure 12 for a graphical depiction of the results). No interactions between NASA-TLX scores and task order were found, $F(9, 81) = 1.71$, $p > .05$, $\eta^2 = .06$.

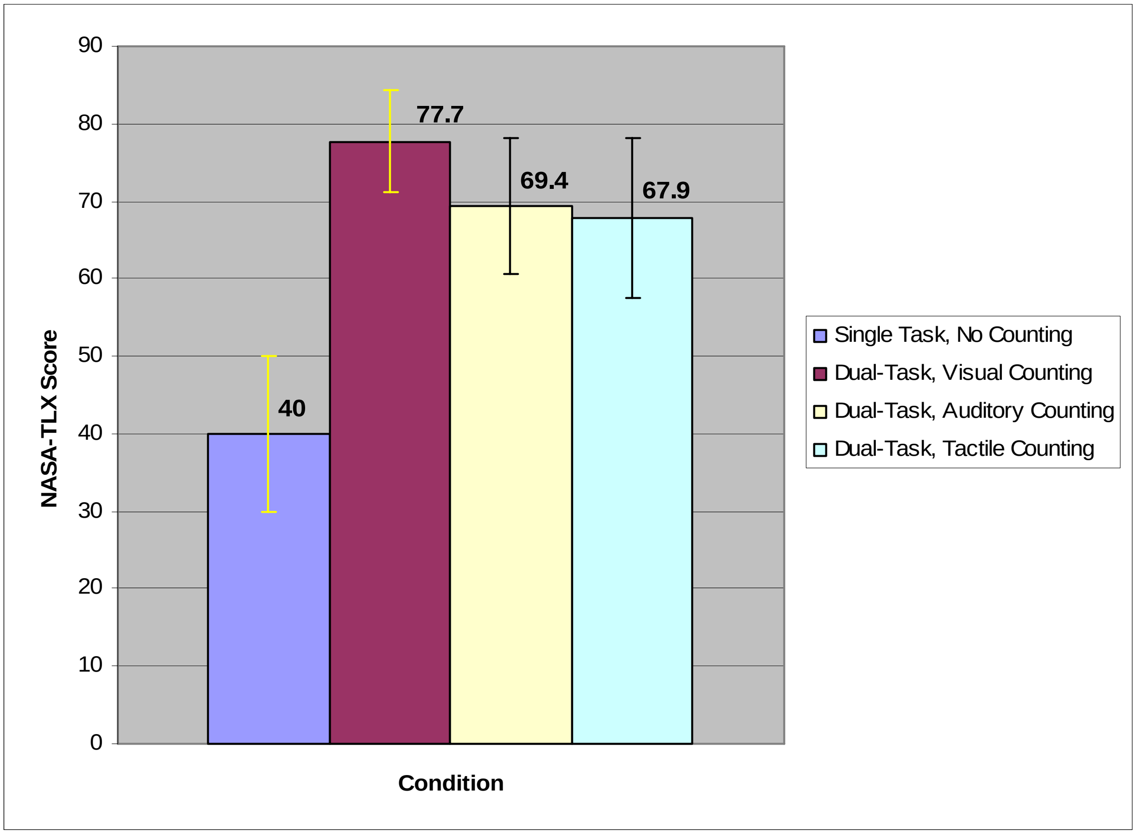

Figure 12. Mean Global NASA-TLX scores by condition. The error bars represent standard deviations.

Additional Analyses

Response times on the MATB were analyzed, the mean values of which can be seen in Table 8.

Table 8. *Mean Response Time for MATB Visual Monitoring Task across Condition.*

Condition	*M*	*SD*	*N*
Single Task, No Counting	2.63	0.97	31
Dual-Task, Visual Counting	3.20	1.15	31
Dual-Task, Auditory Counting	2.68	1.04	31
Dual-Task, Tactile Counting	3.23	1.35	31

A repeated-measures ANOVA was computed, and no differences were observed, indicating that response time did not differ significantly as a function of experimental condition. D-prime and beta were computed for MATB task performance for all four conditions. The descriptive statistics are presented in Tables 9 and 10.

Table 9. *Descriptive Statistics for d-prime for MATB Performance across Condition.*

Condition	*M*	*SD*	*N*
Single Task, No Counting	5.13	1.42	31
Dual-Task, Visual Counting	4.28	1.91	31
Dual-Task, Auditory Counting	5.00	1.88	31
Dual-Task, Tactile Counting	4.40	1.63	31

Table 10. *Descriptive Statistics for beta for MATB Performance across Condition.*

Condition	*M*	*SD*	*N*
Single Task, No Counting	0.93	0.24	31
Dual-Task, Visual Counting	1.10	0.32	31
Dual-Task, Auditory Counting	0.97	0.22	31
Dual-Task, Tactile Counting	1.02	0.32	31

A repeated-measures ANOVA was performed to determine if significant differences were present between d-prime values by condition. No differences were found, $F(3, 90) = 2.1$, $p = .10$. An additional repeated-measures ANOVA was computed to determine if significant differences were present between beta values by condition. A significant main effect of condition was found, $F(3, 90) = 3.43$, $p = .02$, $\eta^2 = .10$ Post hoc analysis (LSD) indicated that beta for MATB performance in the dual visual task condition was significantly higher than that of the single visual task condition ($p < .01$) or of the dual visual-auditory task condition ($p < .05$).

D-prime and beta were computed for M-SWAP performance across all three conditions for which it was incorporated as a secondary task. The descriptive statistics are shown in Tables 11 and 12.

Table 11. *Descriptive Statistics for d-prime for M-SWAP Performance across Condition.*

Condition	*M*	*SD*	*N*
Dual-Task, Visual Counting	1.20	1.05	31
Dual-Task, Auditory Counting	1.93	1.56	31
Dual-Task, Tactile Counting	2.17	1.34	31

Table 12. *Descriptive Statistics for beta for M-SWAP Performance across Condition.*

Condition	*M*	*SD*	*N*
Dual-Task, Visual Counting	1.53	0.54	31
Dual-Task, Auditory Counting	1.16	0.73	31
Dual-Task, Tactile Counting	1.48	1.11	31

A repeated-measures ANOVA was computed to determine if significant differences were present between M-SWAP d-prime values by condition. A significant main effect of condition was found, $F(3, 60) = 7.0$, $p = .002$, $\eta^2 = .19$. Pairwise comparisons (LSD) indicated that participants were significantly more sensitive to tactile counting ($p < .001$) and auditory counting ($p < .05$) than for visual counting. An ANOVA for beta values could not be computed because the wide degree of variance in between conditions, which violated the assumptions for the test.

Discussion

Experiment 2 used a classic secondary loading task paradigm, and consequently, it was necessary to confirm that participants maintained performance on the primary task in order to make certain that the secondary task was consuming reserve capacity. Had the participants reallocated the amount of effort dedicated to the primary task, thereby making allowances for performing the secondary task, then the validity of any comparisons of secondary task performance might be called into question. However, this was not the case; no differences in primary task performance were found using either percent correct or response time as indicators.

It was hypothesized that performance on a secondary auditory or tactile task would be significantly better than performance on a secondary visual task. The data support this hypothesis, and in light of Wickens' model (1984, 2002), it is a reasonable expectation. Additionally, the finding that participants exhibited greater sensitivity to and better performance for the tactile and auditory counting tasks over the visual counting task suggests further that greater attentional capacity was available to perform cross-modal counting. Two visual tasks draw from the same resources, whereas an auditory or tactile task coupled with a visual task draw from different resource pools. The results could also be influenced by the placement of the visual displays, and although they were situated as closely together as possible (combined display area in visual angle subtense was approximately 9.2° horizontally and 22.9° vertically from a distance of 25 in.), it is difficult to perform two visual tasks simultaneously because we can only look in one place at once. However, Burke, Gilson, and Jagacinski (1980) found that people can effectively monitor two visual displays across a variety of spatial separations. Moreover, Wickens' (2002) most recent update to his multiple resource theory suggests people can effectively engage in dual visual tasks if each is presented to a different visual channel (i.e., focal versus ambient vision).

No hypothesis was generated regarding differences between secondary auditory and tactile task performance because there is little basis for these comparisons in the literature. Finding a difference between the two would have lent further support to multiple resource theory, and it would have implied one of two things: 1) the capacities of the auditory and tactile modalities differ, or 2) modality-specific resource pool capacities are interconnected and dependent, meaning drawing from one resource pool can influence the capacity of another. Although no differences were observed in performance and perceived workload between the visual-auditory and visual-tactile task conditions, a slight trend was found in which performance was slightly better and workload was slightly lower for the tactile dual task condition as compared to the auditory condition. A power analysis was performed to determine the sample size required to observe significant differences in M-SWAP performance (percent correct) and perceived workload scores. Assuming a desired power level of .80, a sample of 62 participants would be needed to see a difference in performance; however, the sample size required to observe a difference in perceived workload scores is $N = 164$.

The hypotheses related to perceived workload were supported. Differences were observed between a dual visual-visual task and the other dual task conditions (visual-auditory and visual-tactile). However, no differences in perceived workload were seen between the cross-modal dual task conditions. Given that no performance differences were seen between the two cross-modal dual task conditions, it is not unreasonable to expect perceived workload to follow suit.

The data lead to two possible conclusions. Principally, there are independent resource pools for audition and touch, and their capacities are approximately the same. Alternatively, there is a unitary resource pool (e.g., Kahneman, 1973), and the tasks drew approximately the same quantity of resources as they had comparable levels of demand. At present, there is insufficient basis for a clear preference for one conclusion over the other; however the trend suggesting differential cross-modal capacity is supportive of the former.

CHAPTER 4: GENERAL DISCUSION

The overall purpose of this investigation was to determine if modality-specific attentional resources exist and whether they are independent from one another. Although several aspects of this investigation are unique, it is the inclusion of a loading task incorporating three sensory modalities that is first and foremost. The data support multiple resource theory, though the results are not unassailable due to the potential constraints of monitoring simultaneously two visual displays. Nonetheless, this research led to the validation of a multi-modal secondary task protocol, M-SWAP, which has value from applied and methodological perspectives. The data demonstrate that M-SWAP can be used for assessing attentional reserve capacity for vision, audition, and touch - a capability offered by no other measure (Meshkati, Hancock, Rahimi, & Dawes, 1995).

Applications of this Research

M-SWAP was designed specifically for evaluating attentional reserve capacity in applied environments, and as such, it has the potential for use in many human factors applications. Three exemplars are discussed below:

Multi-Modal Alarm and Display Design

One application is in the domain of multi-modal alarm and display design. Decisions regarding the incorporation of a new alarm or display element in an environment should be data-driven, especially if the capability exists for presenting the new information through different sensory modalities. Human factors practitioners could periodically administer M-SWAP as a secondary loading task while operators perform their current tasks. An analysis of primary and M-SWAP task performance data would indicate through which modality (or modalities) the operators are most receptive to new information. Take the instance of integrating a new alarm in the cockpit of an airplane. The new alarm could be visual, auditory, or tactile in nature. Given the current nature of the cockpit, there is a potential risk that the pilot will fail to detect yet another visual signal from amongst the plethora of visual displays. Further, detection of an auditory alarm could be problematic due to masking from radio communications, other auditory signals, and noise. Consequently, it is reasonable to suspect that a tactile alarm might offer the greatest likelihood of detection provided that the signal is sufficiently louder than ambient noise levels (e.g., vibration of aircraft). However, this decision should be made empirically. Using M-SWAP and high fidelity flight simulation, a pilot could fly through all of the phases of flight, from take-off to landing. M-SWAP would be serve as a secondary task, presenting intermittently visual, auditory, or tactile signals. An analysis the M-SWAP performance data would indicate which modality (or modalities) offers the attentional reserve capacity necessary for reliable detection of the new alarm.

Operator Status Assessment and Adaptive Automation

Another application of M-SWAP is the assessment of operator state. Several factors can influence an operator's capacity for performing a task. Among these are stress, workload, fatigue, and level of expertise (see Hancock & Desmond, 2001). Irrespective of the cause, M-SWAP could be used to evaluate whether an operator's capacity for task performance is compromised or degraded. These data would feed into an adaptive automation system that would either alleviate task demands to match the available capacity or remove them altogether in the event of operator incapacitation.

A specific potential application is an automated drowsy driver countermeasure system. The National Highway Traffic Safety Administration (NHTSA) has estimated that driver fatigue and sleepiness were involved in an average of 56,000 vehicle crashes per year in the United States in the mid-1990s, over 1,500 of which resulted in fatalities (Expert Panel on Driver Fatigue and Sleepiness, 1997). A variety of factors contribute to driver drowsiness, including time of day (Folkard, 1997; Lenné, Triggs, & Redman, 1997; Maycock, 1997), sleep debt (Brown, 1994; Fell & Black, 1997), and vehicular motion itself (Brill, Hancock, & Gilson, 2003; Graybiel & Knepton, 1976; Lawson & Mead, 1998). M-SWAP could be integrated into a vehicle, requiring the driver to perform the task periodically to assess his or her state. Alert drivers would theoretically have the reserve capacity to perform the task. Drowsy (or otherwise impaired) drivers would exhibit performance decrements. In the event their performance failed to meet a predetermined criterion, an automated system would engage to reduce task demands ranging from temporarily disabling distracting technologies (e.g., radio) to safely pulling the car off the road.

Evaluation of Automaticity and Training Effectiveness

As operators become more proficient in performing a task, the performance of the task eventually becomes automatic and requires fewer cognitive resources (Posner & Snyder, 1975). Consequently, automaticity of task performance is associated with increased reserve capacity. Along with primary task performance measures, M-SWAP could be used as a training aid, serving as a secondary indicator of automaticity.

On the subject of automaticity, the data from this study, as well as prior studies using the complex counting task, suggest that performance on M-SWAP does not become automatic. None of the prior studies using the complex counting task have observed learning effects, which is an extraordinary and unique quality among performance measures. This is a topic that should be investigated further. The potential utility of a performance-based assessment measure that is evidently resistant to learning and practice effects is tremendous.

Limitations of the Present Research

There are limitations to the present research, which must be considered when interpreting its results and conclusions. This research uses a multi-modal secondary loading task - a counting task. One of the requirements for selecting a task for these experiments was that the signals provided to participants must be visual, auditory, and tactile in nature. A secondary, but equally important, requirement was that the cognitive component of the task had to be the same, irrespective of the sensory modality through which the signals were presented. These requirements were met through the use of M-

SWAP; however, there are specific implications associated with the use of a counting task, particularly when one looks beyond the levels of attention and sensory coding to short-term/working memory. The signals presented in the counting task were spatial in nature, with the possible exception of the auditory counting task. The auditory counting task was pitch-based, which is an abstraction of spatial separation. The tally of target signals presented was maintained in working memory as a verbal code. This was supported anecdotally by participants who indicated they kept count through subvocal rehearsal (e.g., Baddeley, 2002; Baddeley & Hitch, 1974). It is possible that different results might have been obtained by using a verbal task that required spatial representation; however, this is largely irrelevant. Until a tactile language is developed and there are people who are equally proficient in its use as they are with written language and speech, a task such as a spatial counting task is the most feasible manner of parsing multi-modal attentional allocation and reserve capacity.

Directions for Future Research

There are many directions for future research, but this discussion will be limited to only a few exemplars. From the perspective of methodology, these experiments have exposed a potential flaw in M-SWAP. It was noted in the method section of both experiments that the data for four of the original 36 participants were excluded from analyses because they could not reliably discriminate between the middle and high tones of the auditory counting task. This was not evident in the practice data because only the low demand version was used, which did not require this discrimination. The middle and high tones are 900 Hz and 1800 Hz, respectively, and form a musical octave. An octave represents a doubling of frequency, but they have the same "tone chroma" or note of the musical scale (Blake & Sekuler, 2005). A future investigation should examine developing an alternative auditory counting task. One option is to use pitches in a manner similar to that of the current task, but simply avoid the octave issue by selecting different frequencies. Another option is to use spatial audio, which would, in essence, reform the auditory task to be more analogous to the visual and tactile counting tasks, so that they use signals on the left, center, and right rather than low, middle, and high. Whether a monotone spatialized auditory counting task would be equally effective in imposing the demand as would the pitch-based counting task needs to be determined through empirical testing. Of course, another approach is to keep using the current version of the auditory counting task and simply improve participant selection procedures to make certain they can accurately discriminate the pitches, as the auditory counting task has been established in its current incarnation for over 35 years.

Another direction for future research is to determine if M-SWAP performance is predictive of actual performance in an applied setting. An earlier discussion proposed using M-SWAP as a protocol for assessing an operator's receptivity to alarm or display information. One could use M-SWAP for a preliminary evaluation of signal receptivity and then compare those data against actual signal detection performance. This would provide valuable data regarding the predictive validity of M-SWAP, and it would provide system designers with a powerful tool for making design decisions (such as through what modality an alert or alarm should be presented for the greatest likelihood of detection) based upon direct empirical evidence, rather than "best estimations" from the scientific literature.

The final direction for future research deals with the theoretical issues pertaining to this research. The present work attempted to differentiate attentional reserve capacity through a secondary loading task, but aside from an instance of resource competition for dual visual tasks, no differences were found. It is possible that increasing the demand level of the secondary loading task might reveal differences in reserve capacity. However, there is already evidence of reduced spare capacity in the dual-task scenario. A within-groups cross experiment analysis revealed that the mean percent correct for moderate demand counting was approximately 10-12% lower when performed as a secondary loading task (Experiment 2) as compared to baseline performance as a primary task (Experiment 1), irrespective of modality. This suggests that the amount of resources required for performing the moderate-demand counting task at baseline levels exceeded the available capacity. Therefore, taxing these resources further through use of the high-demand counting task still might not reveal any differences, unless these tasks draw resources at differential rates by modality.

Future research should also investigate modality-specific reserve capacity as a function of the primary task. The primary task used here was a visual monitoring task. It would be interesting to see what patterns of resource availability and competition emerge through use of an auditory or tactile primary task. Moreover, it would be interesting to see how primary tasks requiring different codes (i.e., verbal versus spatial) might influence secondary task performance across modalities.

A final way of examining multi-modal attentional capacity is through sustained attention research rather than a divided-attention approach, as was employed in the present research. M-SWAP could be adapted to serve as a multi-modal vigilance task.

Any modality differences in the vigilance decrement, a decrease in effective vigilance performance across time, would be suggestive of differential attentional capacity.

Summary

This research was designed to investigate the nature of attentional capacity using a multi-modal approach. The first experiment used a counting task as a primary task in order to validate the task. The second experiment used the same counting task as a traditional secondary loading task in tandem with a primary visual monitoring task to gather evidence regarding potential differences in attentional capacity by modality. The results suggest that attentional capacity is multi-modal, and the capacities are approximately the same sizes with a slight trend towards greater capacity for tactile signals. However, the results do not completely preclude the possibility of multi-modal attention being a function of allocation from a unitary resource. Further research is required to investigate these constructs and determine the true nature of our attentional resources.

APPENDIX A: INSTITUTIONAL REVIEW BOARD APPROVAL LETTER

University of Central Florida

Office of Research & Commercialization

January 26, 2006

J. Christopher Brill, Doctoral Student
University of Central Florida
Department of Psychology
PH 302
Orlando, FL 32816-1390

Dear Mr. Brill:

With reference to your protocol #05-3112 entitled, **"Comparison of Multiple Resource Capacities through Use of a Multi-sensory Counting Task,"** I am enclosing for your records the approved, expedited document of the UCFIRB Form you had submitted to our office. **This study was approved on 1/25/06. The expiration date will be 1/24/07.** Should there be a need to extend this study, a Continuing Review form must be submitted to the IRB Office for review by the Chairman or full IRB at least one month prior to the expiration date. This is the responsibility of the investigator. **Please notify the IRB office when you have completed this research study.**

Please be advised that this approval is given for one year. Should there be any addendums or administrative changes to the already approved protocol, they must also be submitted to the Board through use of the Addendum/Modification Request form. Changes should not be initiated until written IRB approval is received. Adverse events should be reported to the IRB as they occur.

Should you have any questions, please do not hesitate to call me at 407-823-2901.

Please accept our best wishes for the success of your endeavors.

Cordially,

Barbara Ward

Barbara Ward, CIM
UCF IRB Coordinator
(FWA00000351, IRB00001138)

Copies: IRB File
Richard Gilson, Ph.D.

BW:jm

12443 Research Parkway • Suite 302 • Orlando, FL 32826-3252 • 407-823-3778 • Fax 407-823-3299

APPENDIX B: NASA-TLX INSTRUCTIONS AND SCRIPTS

NASA-TLX Scripts

First Administration

"I need you to make some ratings regarding the task you just performed. On the first page, place a single vertical mark on each line representing the extent to which that factor influenced your performance. For example, consider how mentally demanding the task was (low versus high) and place a mark on the line. Then, consider how physically demanding the task was (low versus high) and place a mark on the line, and so on. On the second page, circle one member of each pair that indicates which factor influenced your performance the most. For example, consider whether it was more mentally demanding or physically demanding and circle one of the pair. Then consider whether it was more a matter of time pressure (temporal demand) or mental demand that influenced your performance, and so on until one member of each pair is circled. So that you know exactly what I want you to rate, please read over this list of rating scale definitions before making your ratings. Any questions?"

Subsequent Administrations

"I need you to make some ratings regarding the task you just performed. Consider the most recent time you performed the task and place a mark on each line representing the extent to which that factor influenced your performance. Then, on the second page, circle one member of each pair that indicates which factor influenced your performance the most. Please refer to the list of rating scale definitions in case you need reminded of to what each factor refers."

APPENDIX C: ORDER-10 LATIN SQUARE DESIGN WITH TASK SEQUENCES

Order 10 Latin Square

Task Order										
A	1	2	10	3	9	4	8	5	7	6
B	2	3	1	4	10	5	9	6	8	7
C	3	4	2	5	1	6	10	7	9	8
D	4	5	3	6	2	7	1	8	10	9
E	5	6	4	7	3	8	2	9	1	10
F	6	7	5	8	4	9	3	10	2	1
G	7	8	6	9	5	10	4	1	3	2
H	8	9	7	10	6	1	5	2	4	3
I	9	10	8	1	7	2	6	3	5	4
J	10	1	9	2	8	3	7	4	6	5

Order 10 Latin Square (with Condition Assignments)

Task Order										
A	VL	VM	D	VH	TH	AL	TM	AM	TL	AH
B	VM	VH	VL	AL	D	AM	TH	AH	TM	TL
C	VH	AL	VM	AM	VL	AH	D	TL	TH	TM
D	AL	AM	VH	AH	VM	TL	VL	TM	D	TH
E	AM	AH	AL	TL	VH	TM	VM	TH	VL	D
F	AH	TL	AM	TM	AL	TH	VH	D	VM	VL
G	TL	TM	AH	TH	AM	D	AL	VL	VH	VM
H	TM	TH	TL	D	AH	VL	AM	VM	AL	VH
I	TH	D	TM	VL	TL	VM	AH	VH	AM	AL
J	D	VL	TH	VM	TM	VH	TL	AL	AH	AM

Legend

	Modality	Demand
1 = VL	Visual	Low
2 = VM	Visual	Moderate
3 = VH	Visual	High
4 = AL	Auditory	Low
5 = AM	Auditory	Moderate
6 = AH	Auditory	High
7 = TL	Tactile	Low
8 = TM	Tactile	Moderate
9 = TH	Tactile	High
10 = D	Dummy Trial	

APPENDIX D: INFORMED CONSENT STATEMENT

Informed Consent Statement

Project Title: Comparison of Multiple Resource Capacities through Use of a Multi-sensory Counting Task

Primary Investigator(s): Mr. Chris Brill and Dr. Richard Gilson

Overview: This experiment is intended to help develop a new measure of mental workload across the senses. If you choose to participate in this study, you will be asked to perform a counting task in which random signals will be presented visually (blocks on a computer screen), auditorily (musical tones), and tactually (mild vibration against the skin – like a vibrating cell phone or pager). You will be asked to respond by pressing a button.

If I choose to participate, what will I be asked to do?
You will be asked to provide a brief medical history to make sure you are eligible for participation in the study. The history primarily asks about conditions or medications that might be related to sensory deficits (e.g., loss of hearing, reduced skin sensitivity) and motor ability. You may refuse to answer any questions that make you feel uncomfortable.

You will be asked to wear one of the laboratory protective research garments (shirts). Participants are asked to wear our protective garments for two reasons: 1) Because of the construction and expense of the vibration devices (tactors), they cannot easily be cleaned. Therefore, the best way to keep them clean is to prevent them from touching the skin. 2) Since the tactors do not touch the skin, we must standardize the material between the tactors and the skin. This way we can accurately compare participant performance. Of course, you will be given privacy to change into the protective garment.

To ensure accurate placement of the tactors, your abdomen will need to be measured using a cloth measuring tape. The researcher will then fit you with the tactor belt.

The researcher will then seat you at a computer workstation, and you will be provided with more specific instructions on how to perform the counting task. You will have the opportunity to ask for clarification if any aspect of the task is confusing.

Once you are finished with the experiment, the researcher will once again give you privacy to change back into your regular clothes. Since the experiment involves a second session, the researcher will ask you about scheduling a follow-up.

The second experimental session involves performing the same counting task only you will be asked to perform simultaneously a visual monitoring task using a second computer.

What steps are being taken to ensure my privacy?
All information you provide will be kept confidential. Written information (e.g., surveys, forms, etc.) is kept in a locked file cabinet. A numerical code will be used for all electronic information (e.g., performance data) so that your identity cannot be linked with the data file.

Are there any risks associated with participating in this experiment?
The experiment does not require you to perform actions beyond that experienced in everyday life. The tactors used for vibration stimuli are commercially available, and they are not much different from devices used in vibrating cell phones and pagers. Therefore, this protocol is deemed minimal risk.

What if I have questions about the experiment or its procedures?
You may ask questions about the experiment at anytime. If you have questions after the experiment session has ended, you may contact Chris Brill at CATRlab@netscape.net or (407) 823-2298.

Who do I contact if I have questions about participants' rights?
Questions or concerns about the research participants' rights may be directed to the UCFIRB Office, University of Central Florida Office of Research, Orlando Tech Center, 12443 Research Parkway, Suite 302, Orlando, FL 32826. The phone number is (407) 823-2901.

How long does the experiment last?
It varies from person to person, but a typical time commitment for the first session is approximately 1½ hours. The duration for the second session is approximately 1 hour.

Will I receive any compensation for participating in this experiment?
Some instructors offer extra credit for participating in experiments, but this is at your instructor's discretion. If your instructor approves, you will receive extra credit for participating in this experiment. The standard rate in the psychology department is 1 credit for every half hour of participation. If you choose, you can receive monetary compensation instead of extra credit at the rate of $10 per hour.

Is there anything else I need to know?
You must be 18 years of age or older to participate in this experiment. You are free to withdraw from the experiment at anytime without any negative consequences; however, you will only be compensated for the amount of time you spent participating in the experiment.

If you believe you have been injured during participation in this research project, you may file a claim with UCF Environmental Health & Safety, Risk and Insurance Office, P.O. Box 163500, Orlando, FL 32816-3500 (407) 823-6300. The University of Central Florida is an agency of the State of Florida for purposes of sovereign immunity and the university's and the state's liability for personal injury or property damage is extremely limited under Florida law. Accordingly, the university's and the state's ability to compensate you for any personal injury or property damage suffered during this research project is very limited.

I have read the procedure described above. I voluntarily agree to participate in the procedure and I have received a copy of this description.

____
Participant's Signature
Date

___________________________________ _____________________ _______
Witness' Signature (Research Assistant) PI's Signature Date
Date

APPENDIX E: DEMOGRAPHICS AND MEDICAL HISTORY FORMS

UCF Tactile Research Laboratory
Demographics and Medical Questionnaire

This survey was designed to obtain information about our research participants prior to their serving in our studies. We need the medical information to help us interpret your results. This contact information sheet is separated from the rest of your file to maintain confidentiality. ALL data collected in this laboratory is to be kept confidential. This page will be separated from the actual medical history questionnaire so that no one can link the information you provide with your identity. Your contact information will only be used in the event we have some follow-up questions or need to schedule a subsequent laboratory session.

Name: ___________________________________

Address: ___________________________________

____

____

Date: _____________

Sex (circle one): M / F

Age: ___________

Handedness: L / R

Phone Number: ____________________________

E-mail Address: ____________________________

Measurements (taken by experimenter):

Lower Circumference: ________ cm

Medical History Questionnaire

1. Have you had any of the following conditions that affected your arms, wrist, hands, or fingers? If yes, please indicate how much the condition interferes with your activities now and which side:
0= Not at all 1 = A little 3 = A great deal L = Left Side R = Right Side

Skin disorders (e.g., pressure sores, severe burns)	Yes / No	0	1	2	L	R
Peripheral neuropathy	Yes / No	0	1	2	L	R
Carpal Tunnel Syndrome	Yes / No	0	1	2	L	R
Broken/injured (indicate: left arm, wrist, hand, or fingers)	Yes / No	0	1	2	L	R
Cuts requiring sutures (indicate: left arm, wrist, hand, or fingers)	Yes / No	0	1	2	L	R
Pinched Nerve	Yes / No	0	1	2	L	R
Hand-Arm Vibration Syndrome or Vibration White Finger	Yes / No	0	1	2	L	R

Other: ____

2. Have you experienced any numbness, tingling, or pain in your extremities, particularly in your hands and fingers that has not been explained by any of the above conditions? Yes / No

If yes, please explain what body part(s) are affected and to what extent:
____

3. Are you currently taking any medication that might affect your motor coordination, particularly use of your arms, hands, or fingers? Yes / No

If yes, please list below:

Medication Name Reason Taken

____________________________ ________________________________

____________________________ ________________________________

4. Is there anything else (injuries, illnesses) that might affect your ability to use your arms, hands, or fingers? Yes / No

If yes, please explain what body part(s) are affected and to what extent:
____

APPENDIX F: EXAMPLE M-SWAP SCRIPTS WITH TASK INSTRUCTIONS AND COMPUTER COMMANDS

Script for Counting Task: VISUAL

PRACTICE
Type the following: mswap –V –L:1 –S:ID # -D:L

"For this task, you will be presented with a random series of three boxes positioned on the left, center, or right of the screen. Your task is to count the number of times you see the left box, and press the left button after every fourth one. You might occasionally think there is a pattern, but there really isn't one - you really have to count. Do you have any questions? This time you're doing this for practice. To lower the risk of distraction, please place these hearing protectors in your ears."

LOW DEMAND
Type the following: mswap –V –L:5 –S:ID # -D:L

"For this task, you will be presented with a random series of three boxes positioned on the left, center, or right of the screen. Your task is to count the number times you see the left box, and press the left button after every fourth one. Do you have any questions? To lower the risk of distraction, please place these hearing protectors in your ears."

MODERATE DEMAND
Type the following: mswap –V –L:5 –S:ID # -D:M

"For this task, you will be presented with a random series of three boxes positioned on the left, center, or right of the screen. Your task is to count the number of left and center boxes, and press the left and center buttons, respectively, after every fourth one. This means you need to count the number of times you see the left boxes and press the left button after every fourth one, while simultaneously counting the number of times you see the center boxes and pressing the center button after every fourth one. Do you have any questions? To lower the risk of distraction, please place these hearing protectors in your ears."

HIGH DEMAND
Type the following: mswap –V –L:5 –S:ID # -D:H

"For this task, you will be presented with a random series of three boxes positioned on the left, center, or right of the screen. Your task is to count the number of left, center, and right boxes, and press the left, center and right buttons, respectively, after every fourth presentation. This means you need to count the number of times you see the left box and press the left button after every fourth one, while simultaneously counting the number of times you see the center box and pressing the center button after every fourth one, and likewise pressing the right button after every fourth box on the right. Do you have any questions? To lower the risk of distraction, please place these hearing protectors in your ears."

Script for Counting Task: AUDITORY

PRACTICE
Type the following: mswap –A –L:1 –S:ID # -D:L

"For this task, you will be presented with a random series of three pitched tones: low, middle, and high. Your task is to count the number of times you hear the low tone, and press the left button after every fourth one. You might occasionally think there is a pattern, but there really isn't one - you really have to count. Do you have any questions? This time you're doing this for practice. Please put the headphones on now."

LOW DEMAND
Type the following: mswap –A –L:5 –S:ID # -D:L

"For this task, you will be presented with a random series of three pitched tones: low, middle, and high. Your task is to count the number times you hear the low tone, and press the left button after every fourth one.   Do you have any questions? Please put the headphones on now."

MODERATE DEMAND
Type the following: mswap –A –L:5 –S:ID # -D:M

"For this task, you will be presented with a random series of three pitched tones: low, middle, and high. Your task is to count the number of low and middle tones, and press the left and center buttons, respectively, after every fourth one. This means you need to count the number of times you hear the low tone and press the left button after every fourth one, while simultaneously counting the number of times you hear the middle tone and pressing the center button after every fourth one. Do you have any questions? Please put the headphones on now."

HIGH DEMAND
Type the following: mswap –A –L:5 –S:ID # -D:H

"For this task, you will be presented with a random series of three pitched tones: low, middle, and high. Your task is to count the number of low, middle, and high tones, and press the left, center and right buttons, respectively, after every fourth one. This means you need to count the number of times you hear the low tone and press the left button after every fourth one, while simultaneously counting the number of times you hear the middle tone and pressing the center button after every fourth one, and likewise pressing the right button after every fourth high tone. Do you have any questions? Please put the headphones on now."

Script for Counting Task: TACTILE

PRACTICE
Type the following: mswap –T –L:1 –S:ID # -D:L

"For this task, you will be presented with a random series of vibratory taps positioned on the left, center, or right side of your body. Your task is to count the number of times you feel the left tap, and press the left button after every fourth one. You might occasionally think there is a pattern, but there really isn't one - you really have to count. Do you have any questions? This time you're doing this for practice. To lower the risk of distraction, please place these hearing protectors in your ears."

LOW DEMAND
Type the following: mswap –T –L:5 –S:ID # -D:L

"For this task, you will be presented with a random series of vibratory taps on the body positioned on the left, center, or right side of your body. Your task is to count the number of times you feel the left taps, and press the left button after every fourth one. Do you have any questions? To lower the risk of distraction, please place these hearing protectors in your ears."

MODERATE DEMAND
Type the following: mswap –T –L:5 –S:ID # -D:M

"For this task, you will be presented with a random series of vibratory taps positioned on the left, center, or right side of your body. Your task is to count the number of left and center taps, and press the left and center buttons, respectively, after every fourth one. This means you need to count the number of times you feel a left tap and press the left button after every four one, while simultaneously counting the number of times you feel a center tap and pressing the center button after every fourth one. Do you have any questions? To lower the risk of distraction, please place these hearing protectors in your ears."

HIGH DEMAND
Type the following: mswap –T –L:5 –S:ID # -D:H

"For this task, you will be presented with a random series of vibratory taps positioned on the left, center, or right side of your body. Your task is to count the number of left, center and right taps, and press the left, center and right buttons, respectively, after every fourth one. This means you need to count the number of times you feel a left tap and press the left button after every four one, while simultaneously counting the number of times you feel a center tap and pressing the center button after every fourth one, and likewise pressing the right button after every fourth tap on the right. Do you have any questions? To lower the risk of distraction, please place these hearing protectors in your ears."

APPENDIX G: EXPERIMENT 1 SKEWNESS AND KURTOSIS STATISTICS FOR M-SWAP PERCENT CORRECT AND NASA-TLX SCORES

Skewness and Kurtosis Statistics for M-SWAP Percent Correct by Condition

Condition		Skewness		Kurtosis	
Modality, Demand Level	*N*	Statistic	Std. Error	Statistic	Std. Error
Visual, Low Demand	32	-.540	.414	-.830	.809
Auditory, Low Demand	32	-4.468	.414	22.715	.809
Tactile, Low Demand	32	-.948	.414	.333	.809
Visual, Moderate Demand	32	-1.484	.414	3.655	.809
Auditory, Moderate Demand	32	-1.746	.414	2.820	.809
Tactile, Moderate Demand	32	-.855	.414	-.298	.809
Visual, High Demand	32	-.752	.414	-.518	.809
Auditory, High Demand	32	-.921	.414	.773	.809
Tactile, High Demand	32	-1.701	.414	4.272	.809

Skewness and Kurtosis Statistics for Global NASA-TLX Scores by Condition

Condition		Skewness		Kurtosis	
Modality, Demand Level	*N*	Statistic	Std. Error	Statistic	Std. Error
Visual, Low Demand	32	.570	.414	.401	.809
Auditory, Low Demand	32	.738	.414	.396	.809
Tactile, Low Demand	32	-.023	.414	-1.233	.809
Visual, Moderate Demand	32	-.122	.414	-.179	.809
Auditory, Moderate Demand	32	-.132	.414	-.069	.809
Tactile, Moderate Demand	32	-.133	.414	-.389	.809
Visual, High Demand	32	-1.023	.414	.927	.809
Auditory, High Demand	32	-.650	.414	.101	.809
Tactile, High Demand	32	-.490	.414	-.638	.809

APPENDIX H: MATB VISUAL MONITORING TASK INSTRUCTIONS

MATB - Monitoring Task Script

"In this task, you will be required to monitor the upper-left display on your screen for possible malfunctions. This display consists of 4 dials simulating the temperature and pressure gauges of the two engines of an aircraft. T1 represents the Temperature and P1 represents the Pressure of Engine 1. T2 and P2 represent the temperature and pressure of Engine 2. Normally, the pointer indicates a good state of the two engines by fluctuating one mark below or above the central line. However, from time to time, the monitoring system fails, which you will notice whenever the pointer of each of the four dials fluctuates by 2 or more marks *below or above* the central line. When this happens, a red warning light comes on to indicate that a malfunction is about to occur; therefore, you will need to pay attention to this display in order to respond as quickly and accurately as possible."

"Your task is to detect any malfunction(s) in the temperature and pressure dials by pressing the appropriate button as quickly and as accurately as possible. T1 stands for temperature of engine 1 and P1 stands for pressure of engine 1. T2 stands for temperature of engine 2 and P2 stands for pressure of engine 2. Do you have any questions?"

APPENDIX I: EXPERIMENT 2 SKEWNESS AND KURTOSIS STATISTICS FOR MATB PERCENT CORRECT, M-SWAP PERCENT CORRECT, AND GLOBAL NASA-TLX SCORES

Skewness and Kurtosis Statistics for MATB Percent Correct by Condition

Condition	*N*	Skewness		Kurtosis	
		Statistic	Std. Error	Statistic	Std. Error
Single Task, No Counting	31	-1.174	.421	.072	.821
Dual Task, Visual Counting	31	-1.100	.421	.736	.821
Dual Task, Auditory Counting	31	-1.714	.421	2.253	.821
Dual Task, Tactile Counting	31	-.379	.421	-1.279	.821

Skewness and Kurtosis Statistics for M-SWAP Percent Correct by Condition

Condition	*N*	Skewness		Kurtosis	
		Statistic	Std. Error	Statistic	Std. Error
Visual Counting	31	-.124	.427	-1.344	.833
Auditory Counting	31	-.550	.427	-.158	.833
Tactile Counting	31	-.615	.427	-.273	.833

Skewness and Kurtosis Statistics for Global NASA-TLX Scores by Condition

Condition	*N*	Skewness		Kurtosis	
		Statistic	Std. Error	Statistic	Std. Error
Single Task - MATB, No Counting Task	31	.185	.421	-1.028	.821
Dual Task – MATB, Visual Counting Task	31	-.471	.421	.304	.821
Dual Task – MATB, Auditory Counting Task	31	-.552	.421	-.251	.821
Dual Task – MATB, Tactile Counting Task	31	-.883	.421	.218	.821

REFERENCES

Allen G., Buxton, R. B., Wong, E. C., Courchesne, E. (1997). Attentional activation of the cerebellum independent of motor involvement. *Science, 275,* 1940–1943.

Baddeley, A. (1992). Working memory. *Science, 255,* 395-406.

Baddeley, A. D., & Hitch, G. (1974). Working memory. In G. Bower (Ed.), *Recent advances in learning and motivation (Vol. 8)*. New York: Academic Press.

Bischoff-Grethe, A., Ivry, R. B., & Grafton, S. T. (2002). Cerebellar involvement in response reassignment rather than attention. *Journal of Neuroscience, 22,* 546-553.

Blake, R., & Sekuler, R. (2005). *Perception* (5th Ed.). McGraw-Hill: New York, NY.

Brill, J. C., Hancock, P. A., & Gilson, R. D. (2003). Driver drowsiness: Is something missing? *Proceedings of the 2nd International Symposium on Human Factors in Driver Assessment, Training, and Vehicle Design,* Park City, UT, 138-142.

Brill, J. C., Mouloua, M., Hancock, P. A., Gilson, R. D., & Kennedy, R. S. (2003). A protocol for assessing reserve cognitive capacity in complex systems. *Proceedings of the 6th International Conference on Naturalistic Decision Making,* Pensacola, FL.

Brown, I. D. (1994). Driver fatigue. *Human Factors, 36*(2), 298-314.

Burke, M. W., Gilson, R. D., & Jagacinski, R. J. (1980). Multi-modal information processing for visual workload relief. *Ergonomics, 23,* 961-975.

Burton, H., & Sinclair, R. J. (2000). Tactile-spatial and cross-modal attention effects in the primary somatosensory cortical areas 3b and 1-2 of rhesus monkeys. *Somatosensory & Motor Research, 17,* 213-228.

Burton, H., Sinclair, R., Hong, S.-Y., Pruett, J. J., & Whang, K. (1997). Tactile-spatial and cross-modal atentioneffects in the second somatosensory and 7b cortical areas of rhesus monkeys. *Somatosensory & Motor Research, 14,* 237-267.

Cholewiak, R. C., Brill, J. C., & Schwab, A. (2004). Vibrotactile localization on the abdomen: Effects of place and space. *Perception & Psychophysics, 66*(6), 970-987.

Cohen, J. (1977). *Statistical power analysis for the behavioral sciences* (revised edition). New York: Academic Press.

Comstock, J. R., & Arnegard, R. J. (1992). *The multi-attribute task battery for human operator workload and strategic behavior research* (Rep. No. 104174). Hampton, Virginia: Langley Research Center, National Aeronautics and Space Administration.

Courchesne, E., Townsend, J., Akshoomoff, N. A., Saitoh, O., Yeung-Courchesne, R., Lincoln, A. J., James, H. E., Haas, R. H., Schreibman, L., & Lau, L. (1994) Impairment in shifting attention in autistic and cerebellar patients. *Behavioral Neuroscience, 108,* 848–865.

Deutsch, J. A., & Deutsch, D. (1963). Attention: Some theoretical considerations. *Psychological Review, 70,* 51-61.

Driver, J., & Spence, C. (1998). Attention and the crossmodal construction of space. *Trends in Cognitive Sciences, 2,* 254-262.

Duncan, J., Martens, S., & Ward, R. (1997). Restricted attentional capacity within but not between sensory modalities. *Nature, 387,* 808-810.

Eimer, M., & Driver, J. (2000). An event-related brain potential study of cross-modal links in spatial attention between vision and touch. *Psychophysiology, 37,* 697-705.

Eimer, M., & Forster, B. (2003). The spatial distribution of attentional selectivity in touch: Evidence from somatosensory ERP components. *Clinical Neurophysiology, 114,* 1298-1306.

Eimer, M., & van Velzen, J., & Driver, J. (2002). Cross-modal interactions between audition, touch, and vision in endogenous spatial attention: ERP evidence on preparatory states and sensory modulations. *Journal of Cognitive Neuroscience, 14,* 254-271.

Expert Panel on Driver Fatigue and Sleepiness (1997). *Drowsy driving and automobile crashes.* Retrieved April 3, 2002 from http://www.nhtsa.dot.gov.

Fell, D. L., & Black, B. (1997). Driver fatigue in the city. *Accident Analysis and Prevention, 29*(4), 463-469.

Folkard, S. (1997). Black times: Temporal determinants of transportation safety. *Accident Analysis and Prevention, 29*(4), 417-430.

Gescheider, G. A., Capraro, A. J., Frisina, R. D., Hamer, R. D., & Verrillo, R. T. (1978). The effects of a surround on vibrotactile thresholds. *Sensory Processes, 2,* 99-115.

Graybiel, A., & Knepton, J. (1976). Sopite syndrome: A sometimes sole manifestation of motion sickness. *Aviation, Space, and Environmental Medicine, 47,* 873-882.

Green, D. M., & Swets, J. A. (1966). *Signal detection theory and psychophysics.* John Wiley and Sons: New York.

Hancock P. A., & Desmond, P. A. (2001). *Stress, workload, and fatigue.* Mahwah, NJ: Lawrence Erlbaum Associates.

Hancock, P. A., & Warm, J. S. (1989). A dynamic model of stress and sustained attention. *Human Factors, 31,* 519-537.

Hart, S., & Staveland, L. (1988). Development of the NASA-TLX: Results of empirical and theoretical research. In P. Hancock and N. Meshkati (Eds.), *Human mental workload.* Amsterdam: North-Holland.

Isreal, J. (1980). *Structural interference in dual task performance: Behavioral and electrophysiological data.* Unpublished PhD dissertation, University of Illinois, Urbana-Champaign.

James, W. (1890). *Principles of psychology, Vol. 1.* New York: Holt.

Jerison, H. J. (1955). *Effect of a combination of noise and fatigue on a complex counting task* (Rep. No. WADC TR-55-360). Dayton, Ohio: Wright Air Development Center, Wright Patterson AFB.

Jerison, H. J. (1956). *Differential effects of noise and fatigue on a complex counting task* (Rep. No. WADC TR-55-359). Dayton, Ohio: Wright Air Development Center, Wright Patterson AFB.

Johnston, W., & Heinz, S. (1978). Flexibility and capacity demands of attention. *Journal of Experimental Psychology, General, 107,* 420-435.

Kahneman, D. (1973). *Attention and effort.* Englewood Cliffs, NJ: Prentice-Hall.

Kennedy, R. S. (1971). A comparison of performance on visual and auditory monitoring tasks. *Human Factors, 13*(2), 93-97.

Kennedy, R. S., & Bittner, A. C. (1980). Development of performance evaluation tests for environmental research (PETER): Complex counting test. *Aviation, Space, and Environmental Medicine, 51,* 142-144.

Lawson, B. D., & Mead, A. M. (1998). The sopite syndrome revisited: Drowsiness and mood changes during real or apparent motion. *Acta Astronautica, 43,* 181-192.

Lenné, M. G., Triggs, T. J., & Redman, J. R. (1997). Time of day variations in driving performance. *Accident Analysis and Prevention, 29*(4), 431-437.

Macaluso, E., Frith, C., & Driver, J. (2000). Selective spatial attention in vision and touch: Unimodal and multimodal mechanisms revealed by PET. *Journal of Neurophysiolology, 83,* 3062-3075.

Macmillan, N. A., & Creelman, C. D. (2005). *Detection theory: A user's guide* (2nd Ed.). Mahwah, NJ: Lawrence Erlbaum Associates.

Maycock, G. (1997). Sleepiness and driving: the experience of U.K. car drivers. *Accident Analysis and Prevention, 29*(4), 453-462.

Meshkati, N., Hancock, P. A., Rahimi, M., & Dawes, S. M. (1995). Techniques in mental workload assessment. In J. R. Wilson and E. N. Corlett, (Eds.), *Evaluation of human work: A practical ergonomics methodology* (pp. 749-782). Taylor & Francis, Philadelphia, PA.

Moray, N. (1967). Where is capacity limited? A survey and a model. *Acta Psychologica, 27,* 84-92.

Mouloua, M., Rinalducci, E., Hancock, P. A., & Brill, J. C. (2003). Evaluating workload associated with telematic devices via a secondary task protocol. *Proceedings of the 2nd International Symposium on Human Factors in Driver Assessment, Training, and Vehicle Design,* Park City, UT, 67-68.

Navon, D., & Gopher, D. (1979). On the economy of the human processing system. *Psychological Review, 86,* 254-255.

Norman, D., & Bobrow, D. (1975). On data-limited and resource-limited processing. *Journal of Cognitive Psychology, 7,* 44-60.

Ogden, G. D., Levine, J. M., & Eisner, E. J. (1979). Measurement of workload by secondary tasks. *Human Factors, 21,* 529-548.

Parasuraman, R . (1979). Memory load and event rate control sensitivity decrements in sustained attention. *Science, 205,* 924-927.

Parkes, A. M., & Coleman, N. (1990). Route guidance systems: A comparison of methods of presenting directional information to the driver. In E. J. Lovesey (Ed.), *Contemporary ergonomics 1990* (pp. 480-485). Mahwah, NJ: Erlbaum.

Posner, M. I., & Boies, S. J. (1971). Components of attention. *Psychological Review, 78*(5), 391-408.

Posner, M. I., Nissen, M. J., & Klein, R. M. (1976). Visual dominance: An information processing account of its origins and significance. *Psychological Review, 83,* 157-171.

Posner, M. I., & Snyder, C. R. R. (1975). Facilitation and inhibition in the processing of signals. In P. M. A. Rabbitt & S. Dornic (Eds.), *Attention and performance* (pp. 669-682). New York, Academic Press.

Proctor, R. W. (1978). Attention and modality-specific interference in visual short-term memory. *Journal of Experimental Psychology: Human Perception and Performance, 4*(3), 239-245.

Proctor, R. W., & Proctor, J. D. (1979). Secondary task modality, expectancy, and the measurement of attentional capacity. *Journal of Experimental Psychology: Human Perception and Performance, 5*(4), 610-624.

Ravizza, S. M., & Ivry, R. B. (2001) Comparison of the basal ganglia and cerebellum in shifting attention. *Journal of Cognitive Neuroscience, 13,* 285–297.

Raymond, J. E, Shapiro, K. L., & Arnell, K. M. (1992). Temporary suppression of visual processing in an RSVP task: An attentional blink? *Journal of Experimental Psychology. Human Perception and Performance, 18*(3), 849-860.

Robinson-Riegler, G., & Robinson-Riegler, B. (2004). *Cognitive psychology: Applying the science of the mind.* Boston: Pearson.

Rock, I., & Victor, J. (1964). Vision and touch: An experimentally created conflict between the senses. *Science, 143,* 594-596.

Rolfe, J. M. (1973). The secondary task as a measure of mental load. In W. T. Singelton, J. G., Fox, & D. Whitfield (Eds.), *Measurement of man at work* (pp. 135-148). London: Taylor & Francis.

Rollins, H. A., & Hendricks, R. (1980). Processing of words presented simultaneously to eye and ear. *Journal of Experimental Psychology: Human Perception and Performance, 6*(1), 99-109.

Schiffman, H. R. (1996). *Sensation and perception: An integrated approach* (4th Ed.). New York: John Wiley and Sons, Inc.

Shapiro, K., Arnell, K., & Raymond, J. (1997). The attentional blink. *Trends in Cognitive Sciences, 1*(8), 291-296.

Spelke, E., Hirst, W., & Neisser, U. (1976). Skills of divided attention. *Cognition, 4,* 215-230.

Stevens, S.S. (1959). Cross-modality validation of subjective scales for loudness, vibration, and electric shock. *Journal of Experimental Psychology, 57,* 201-209.

Talsma, D., Doty, T., Strowd, R., & Woldorff, M. (2006). Attentional capacity for processing concurrent stimuli is larger across sensory modalities than within a modality. *Psychophysiology, 43*(6), 541-549.

Wickens, C. D. (1976). The effects of divided attention on information processing in manual tracking. *Journal of Experimental Psychology: Human Perception and Performance, 2*(1), 1-13.

Wickens, C. D. (1984). Processing resources in attention. In R. Parasuraman & R.Davies (Eds.), *Varieties of attention* (pp. 63-101). New York: Academic Press.

Wickens, C. D. (2002). Multiple resources and performance prediction. *Theoretical Issues in Ergonomic Science, 3*(2), 159-177.

Williams, E. J. (1949). Experimental designs balanced for the estimation of residual effects of treatments. *Australian Journal of Scientific Research, A2,* 149-168.

Young, M. S., & Stanton, N. A. (2002). Malleable attentional resources theory: A new explanation for the effects of mental underload on performance. *Human Factors, 44,* 365-375.